JRC Scientific and Technical Reports

Scientific, Technical and Economic Committee for Fisheries (STECF)

Report of the Working Group on Harvest Control Rules (SGRST 08-02)

9 - 13 JUNE, 2008, LOWESTOFT, UK

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EUR 23641 EN - 2008

EUROPEAN COMMISSION

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JRC 49098

EUR 23641 EN
ISBN 978-92-79-10478-7
ISSN 1018-5593
DOI 10.2788/38645

Luxembourg: Office for Official Publications of the European Communities

Printed in Italy

TABLE OF CONTENTS

COMMISSION STAFF WORKING DOCUMENT

HARVEST CONTROL RULES (SGRST-08-02)

SUBGROUP ON STOCK REVIEWS OF THE SCIENTIFIC, TECHNICAL AND ECONOMIC COMMITTEE FOR FISHERIES (STECF)

STECF OPINION EXPRESSED DURING THE PLENARY MEETING

OF 7-11 JULY IN HELSINKI

1. INTRODUCTION

For a number of fish stocks, a number of long-term management plans have been agreed and implemented. For those stocks not yet subject to long-term plans, the Commission must propose fishing opportunities that are sustainable inter alia in biological terms (i.e. taking these fishing opportunities does not adversely affect the ability of future generations to meet their own needs).

In 2007 STECF simulates the consequences of applying a set of harvest control rules (HCRs) whose aims were to ensure that future fishing opportunities were sustainable. Following STECF advice in 2007 (STECF/SGMOS-07-07 Evaluation of "Policy Statement" Harvest Rules report, 10-14 September 207, Charlottenlund), the Commission has proposed a new set of candidate HCRs and seeks advice on the consequences of applying the rules set out in the following terms of reference.

2. TERMS OF REFERENCE

STECF is requested to evaluate:

- the likely consequences of the application of such rules, for a typical range of biological stock situations currently encountered in Community waters;

- the consequences should be evaluated in terms of future yields and future risks to the biological resources;

- available information concerning the typical economic consequences of applying these decision rules should be provided;

STECF is also invited to provide suggestions for changes to the rules in order to improve long-term yields, reduce costs, and to improve the stability of fishing operations and markets.

Rule	Scientific advice	Action to take in setting TAC
1)	Stock exploited consistently with maximum sustainable yield.	Aim to set the TAC to the forecast catch corresponding to the fishing mortality that will deliver the highest yield in the long term[1], **but** do not change the TAC by more than 25%.
2)	Stock overexploited compared to maximum sustainable yield but inside safe biological limits.	Aim to set the TAC to the higher value of (a) to the forecast catch corresponding to taking the highest yield in the long term[1], or (b) continuing to fish at an unchanged mortality rate, **but** do not change the TAC by more than

Rule	Scientific advice	Action to take in setting TAC
		15%.
3)	Stock outside safe biological limits	Aim to set the TAC to the forecast catch that will result in a 30% reduction in fishing mortality rate, **but** do not decrease the fishing mortality so far as to prejudice long-term yields[1] **and** do not reduce the TAC by more than 20%.
4)	Stock is subject to long-term plan and scientists advise on the catch that corresponds to the plan.	The TAC must be set by following the relevant plan.
5)	State of the stock not known precisely and STECF advises on an appropriate catch level.	Aim to set the TAC according to STECF advice **but** do not change the TAC by more than 15%.
6)	State of the stock not known precisely and STECF advises to reduce fishing effort.	The TAC should be reduced by up to 15% and STECF should be asked to advise on the appropriate level of effort.
7)	State of the stock not known precisely and STECF advises the stock is increasing	The TAC should be increased by up to 15%.
8)	State of the stock not known precisely and STECF advises the stock is decreasing	The TAC should be decreased by up to 15%.
9)	STECF advises a zero catch, a reduction to the lowest possible level or similar advice.	The TAC should be reduced by at least 25%. Recovery measures should be implemented including effort reductions and introduction of more selective fishing gear as appropriate.
10)	There is no STECF advice.	While advice is being developed, TACs should be adjusted towards recent real catch levels but should not be changed by more than 15% per year **or** relevant Member States should develop an implementation plan to allow advice to be provided within a short time-frame.

3. STECF OBSERVATIONS AND COMMENTS

Approach and methodology of the WG

STECF notes the considerable amount of work achieved by the Working Group in addressing the terms of reference, which were ambitious. The improvements in the FLR framework have made it much easier to implement and simpler to run Management Strategy Evaluations.

[1] As measured by the fishing mortality corresponding to a marginal yield of 10% of the marginal yield at fishing mortality close to zero ($F_{0.1}$).

The WG report provides a evaluation of 34 different harvest rules scenarios for setting TACs for two generalised fish stocks with different life history parameters “cod-oid” and “her-oid”. These scenario evaluations fall into two main groups:

1 Evaluations of HCR rules based on the results from analytical assessments (VPA-based rules). Three rules were evaluated corresponding to rules 1, 2 and 3 in the Terms of Reference (see Table above).

2 Evaluations of HCR rules when no analytical assessment is available corresponding to Rules 5-10 above.

STECF notes that the Working Group's approach and methodology with respect to modelling the stock’s response to varying rates of exploitation represents the "state of the art" for the evaluation of proposed management strategy rules. However, a bio-economic approach with full feedback of fisher’s behaviour as a result of economic considerations would provide a more comprehensive evaluation tool.

Wider understanding and knowledge of the FLR framework would undoubtedly be of benefit in helping STECF respond to requests for advice on a variety of fisheries management issues. This may need further financial support from EU so that the methodology will become more familiar for scientists and other stakeholders.

STECF notes that, due to time limitations, a number of simulation runs that were envisaged were not undertaken. However, STECF considers that undertaking additional simulations with the same input data and assumptions is unlikely to affect the general findings and conclusions presented in the report. The FLR methodology used was developed in EU funded projects FEMS, EFIMAS and COMMIT, and has been further developed and applied in several other projects, and also in ICES working groups.

The WG simulations were mainly carried out using “basic assumptions” for the operational models with simple random noise in input parameters. There may be a need to test different HCRs to take into account environmental changes and/or stock productivity changes over short and longer-term periods, and test how well the assessment model and the HCR perform under such conditions. However, this activity may be carried out using case studies of specific management plans with plausible stock-specific hypothesis

A test on how well the assessment models can estimate Fmsy and inclusion of Fmsy as a target in the HCR, instead of using proxies like F 0.1, would also be a useful analysis. This should be done for a high number of species and also consider whether stock specific reference points could be replaced by e.g. species specific F – reference points. Meta-analysis of stock productivity may be useful elements of such activity.

STECF notes, that the methodology and HCRs have been applied to only two generic species types: herring-like and cod–like. STECF agrees with the WG that the HCR should be tested for other species types e.g. deep water species (often very long life cycles) and short-lived species. STECF notes also, that FLR has been mainly applied to single species investigations. However, e.g. Ecosystem Approach to Fisheries Management often means that multi-species management tasks need to be considered. Understanding that computational limitations exist, STECF endorses the further development of the present methodology to allow the evaluation of multi-species impacts.

STECF notice that the economic outputs are provided in the model. However no information is provided on the economic part of the model, therefore it is not possible to evaluate the economic outcomes of the model.

Based on the results presented in the report STECF has serious reservations on the validity of the economic outputs and the methodology used. STECF suspects that the economic part of the model was just the calculation of economic indicators based on biology. Thus, no economic behaviour was taken into account and fed back into the biological model. STECF stresses that the outcomes of bio-economic models critically depend on the production function (cost structure and dependencies on e.g. effort and landings) used. The model assumes that the agreed TAC will be caught irrespective of the economic situation. In the report no assumptions are given for the economic part of the model and taking into account these reservations, STECF considers that the results may be misleading.

STECF note that the group only used revenues and net profit as economic indicators. STECF regards this insufficient for a proper economic evaluation of the HCRs.

STECF notes that although the WG adopted only a simple approach to the evaluation of economic performance under the different HCRs, the FLR framework provides the capability to employ more sophisticated economic elements, which are an increasingly important aspect of STECF activities. STECF suggests that in addition to the application of existing economic modules within the FLR framework, the development of additional economic modules be encouraged for future use.

Policy Conclusions of the WG

1. Cases where the HCR is based on results of an analytical assessment – VPA based rules

a) Rule – Set a TAC in line with a fishing mortality rate that is the Maximum of $F_{0.1}$ or F_{sq}

The HCR rule that prescribes setting a TAC in line with a fishing mortality rate corresponding to the maximum of $F_{0.1}$ and F_{sq} often leads to some rebuilding and recovery. However, it often fails to improve situations where overfishing is occurring and even constitutes a risk to well managed stocks. In these cases the rule either maintains fishing mortality at too high a level, preventing recovery, or it leads to a gradual increase in fishing mortality leading to slow stock declines. The HCR can become stuck on relatively high fishing mortality rates that can harm or continue to harm stocks. This occurred because the F_{sq} was often too high to be sustainable.

By including a change in the selectivity on immature fish the negative effects of this HCR can be slightly muted but not sufficient to enable this HCR to be recommended. STECF notes that such result is very likely dependent on the degree of change in selectivity.

STECF considers this approach to be a risky strategy compared to a strategy of setting a TAC in line with $F_{0.1}$.

b) Rule - Set a TAC in line with a fishing mortality rate of $F_{0.1}$

By altering the HCR to select $F_{0.1}$ as the response to each assessment, the HCR became more reliable in terms of maintaining well-managed stocks and recovering stocks that had experienced overfishing or were being overfished. This recovery occurred even in the face of a retrospective bias (brought about by a linear increase imposed on catchability through time), although the improvements and level of rebuilding were often reduced. This HCR would often lead to a reduction in yields for the first few years after the introduction of management. However, the significant reduction in fishing mortality led directly to a significant reduction in costs so the profitability of each fishery tended to be maintained. The amount of benefits is likely to be dependent on the cost structure of the fleet.

Within the time constraints of the workshop this HCR was reasonably well examined. However, there were numerous configurations of Operating Model, Management Procedure (HCR), and Observation Error Model that were not considered and before finally recommending this strategy for use in management it would be sensible to complete at least some of the missing combinations and to test the rule for deep water species and short living species. Especially, there is a need to test how well simple criteria like F 0.1 function in economic terms. This type of further analysis need not necessarily be done in a workshop environment. It would be a useful addition to consider the effect of including a decrease in the selectivity on immature fish on this version of the VPA based HCRs and to test larger changes of selectivity.

2. Cases where the HCR is based on a time series of cpue data

Rule – model-free HCR

There remain many stocks for which there is little data. The model free HCR examined proved to be incapable of maintaining a well managed stock and so could not be recommended. However, such empirical control rules can now be implemented easily within the FLR framework, so it is recommended that further work be aimed at exploring alternative formulations that might provide positive management advice for data poor situations. In addition, there are many stocks (deep-water species; short-lived species; invertebrate species) for which the present HCR formulations are unlikely to be helpful. It is suggested that further work be focussed on examining the management options for such species.

3. Operational Conclusions of the WG

The FLR framework has now been developed to a highly usable level and STECF endorses its use. This present work has stimulated the inclusion of an implementation of an auto-differentiation module that speeds many of the assessment calculations. Now 100 iterations within a scenario may take between 20 and 30 minutes rather than 5 to 8 hours as in the previous version. In addition, it has become much easier to implement different harvest control rules and simpler to run the Management Strategy Evaluations.

These improvements mean that Management Strategy Evaluation becomes a serious option for particular species within European fisheries. FLR has reached its current stage of sophistication and speed and a useful strategy would be to apply the MSE methodology to particular species, stocks, and fisheries. The complexities of particular fisheries and singular stocks could be approached within the FLR framework. The complexities of particular fisheries and singular stocks could be approached within the FLR framework.

STECF conclusions and recommendations

STECF concludes that for stocks for which an analytical assessment of the state of the stock is available (rules 1, 2 and 3 in the Terms of Reference), the results of simulations indicate that for overfished stocks (in relation to long-term yield) within safe biological limits, setting the TAC resulting from the application of a target fishing mortality equal to the higher of $F_{0.1}$ or $F_{sq,}$ often fails to lead to any improvement. Furthermore, this strategy also constitutes a risk to stocks that are initially in a well-managed state.

STECF further concludes that a HCR that prescribes setting the TAC resulting from a fishing mortality consistent with F0.1 performs significantly better. Performance in terms of the development in yield and stock biomass for overfished stocks is improved and the risk to well-managed stocks is reduced considerably.

STECF concludes that for stocks for which an analytical assessment is not available the results of simulations using the model-free HCR of setting a TAC in line with a trend in cpue, proved to be incapable of maintaining a well managed stock and cannot be recommended.

STECF considers that Gross Value Added (GVA) is an important economic indicator and recommends that estimates of GVA be provided in future management strategy evaluations.

STECF recommends that management strategy evaluations be developed that assess more fully the economic performance of different strategies. Ideally, economic behaviour should be incorporated in the simulation modelling to enable feedback between developments in the stock and the fishery.

ANNEX I

STECF/ SGRST-08-02 WORKING GROUP REPORT ON

HARVEST CONTROL RULES

Lowestoft, 9-13 JUNE 2008

This report is the opinion of the expert working group on Harvest Control Rules (STECF/ SGRST-08-02) and not of the Scientific, Technical and Economic Committee for Fisheries (STECF)

This report does not necessarily reflect the view of the European Commission and in no way anticipates the Commission's future policy in this area

4. INTRODUCTION

4.1. Terms of reference

For those stocks not yet subject to long-term plans, the Commission must propose fishing opportunities that are sustainable *inter alia* in biological terms (i.e. taking these fishing opportunities does not adversely affect the ability of future generations to meet their own needs).

Following STECF advice in 2007, the Commission seeks advice on the consequences of applying the rules set out in the annexed table.

STECF is requested to evaluate:

- the likely consequences of the application of such rules, for a typical range of biological stock situations currently encountered in Community waters;

- the consequences should be evaluated in terms of future yields and future risks to the biological resources;

- available information concerning the typical economic consequences of applying these decision rules should be provided;

STECF is also invited to provide suggestions for changes to the rules in order to improve long-term yields, reduce costs, and to improve the stability of fishing operations and markets.

	Scientific advice	**Action to take in setting TAC**
1)	Stock exploited consistently with maximum sustainable yield.	Aim to set the TAC to the forecast catch corresponding to the fishing mortality that will deliver the highest yield in the long term[1], **but** do not change the TAC by more than 25%.
2)	Stock overexploited compared to maximum sustainable yield but inside safe biological limits.	Aim to set the TAC to the higher value of (a) to the forecast catch corresponding to taking the highest yield in the long term[1], or (b) continuing to fish at an unchanged mortality rate, **but** do not change the TAC by more than 15%.
3)	Stock outside safe biological limits	Aim to set the TAC to the forecast catch that will result in a 30% reduction in fishing mortality rate, **but** do not decrease the fishing mortality so far as to prejudice long-term yields[2] **and** do not reduce the TAC by more than 20%.
~~4)~~	Stock is subject to long-term plan and scientists advise on the catch that corresponds to	The TAC must be set by following the relevant plan.

[2] As measured by the fishing mortality corresponding to a marginal yield of 10% of the marginal yield at fishing mortality close to zero ($F_{0.1}$).

	Scientific advice	Action to take in setting TAC
	the plan.	
5)	State of the stock not known precisely and STECF advises on an appropriate catch level.	Aim to set the TAC according to STECF advice **but** do not change the TAC by more than 15%.
6)	State of the stock not known precisely and STECF advises to reduce fishing effort.	The TAC should be reduced by up to 15% and STECF should be asked to advise on the appropriate level of effort.
7)	State of the stock not known precisely and STECF advises the stock is increasing	The TAC should be increased by up to 15%.
8)	State of the stock not known precisely and STECF advises the stock is decreasing	The TAC should be decreased by up to 15%.
9)	STECF advises a zero catch, a reduction to the lowest possible level or similar advice.	The TAC should be reduced by at least 25%. Recovery measures should be implemented including effort reductions and introduction of more selective fishing gear as appropriate.
10)	There is no STECF advice.	While advice is being developed, TACs should be adjusted towards recent real catch levels but should not be changed by more than 15% per year **or** relevant Member States should develop an implementation plan to allow advice to be provided within a short time-frame.

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5. SIMULATION FRAMEWORK

A Management Strategy Evaluation (MSE) approach was taken using the FLR (Fisheries Library for R, http://www.flr-project.org) simulation framework (Kell et al. 2007). The three main elements of a MSE are the

(i) Operating Model (OM), that represents alternative plausible hypotheses about stock and fishery dynamics, allowing integration of a higher level of complexity and knowledge than is generally used within stock assessment models;

(ii) Observation Error Model (OEM) that describes how simulated fisheries data, or pseudo-data, are sampled from the Operating Model; and

(iii) the Management Procedure (MP) or management strategy which is the combination of the available pseudo-data, the stock assessment used to derive estimates of stock status and the management model or Harvest Control Rule (HCR) that generates the management outcomes, such as a target fishing mortality rate or Total Allowable Catch.

An important aspect of management strategy evaluation is that the management outcomes from the HCR are fed back into the operating model so that their influence on the simulated stock and hence on the future simulated fisheries data is propagated through the stock dynamics (Figure 1). All terminology employed here is based upon that of Rademeyer et. al. (2007).

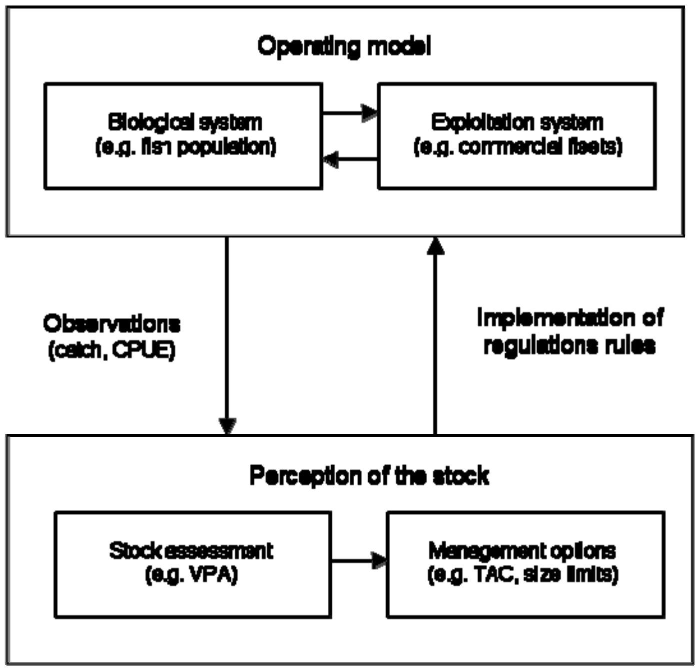

Figure 1. Conceptual framework of the simulation model (after Kell *et al*. (2005a).

So that the benefits of alternative actions (i.e. data collection, stock estimation methods and HCRs) can be compared against each other, a set of common Operating Models (OMs) will be used. These will be based upon those previously developed by the STECF Working Group On Evaluation Of "Policy Statement" Harvest Rules (STECF, 2007b).

The success or otherwise of the MSE framework depends on the extent to which the true range of uncertainty can be identified and represented in the operating models. Several authors (e.g. Rosenberg and Restrepo 1994, Francis and Shotton 1997, Kell *et al*. 2005a, b, 2006a, b) have attempted to identify and categorize the uncertainties that can hinder attempts to manage fisheries (and other natural resources) successfully. These uncertainties include the following (taken from Kell *et al*. 2006a):

process error **–** natural variation in dynamic processes such as recruitment, somatic growth, natural mortality, and the selectivity of the fishery;

observation error **–** related to collecting data from a system (e.g. age sampling, catches, surveys);

estimation error – related to estimating parameters, both in the operating model, and, if a model-based management procedure is used, in the assessment model within the management procedure that leads to the perception of current resource status;
model error – related to uncertainty about model structure (e.g. causal assumptions of the models), both in the operating model and in the management procedure; and
implementation error – because management actions are never implemented perfectly and may result in realised catches that differ from those intended.

5.1. Operational Improvements

Management Strategy Evaluations are by their nature time-intensive. Developing the simulations required to provide the comparative advice about alternative potential management strategies or Harvest Control Rules usually takes a significant amount of time and it would be unusual to attempt to conduct a serious MSE in a one-week workshop environment. The work conducted during the first STECF Working Group On Evaluation Of "Policy Statement" Harvest Rules (STECF, 2007b) was ambitious. The work attempted in this second STECF Working Group Evaluating Harvest Control Rules was much more ambitious. It would not have been possible to conduct the present work had the Management Strategy Evaluation (MSE) framework developed during the first STECF Working Group On Evaluation Of "Policy Statement" Harvest Rules (STECF, 2007b) not been improved. The framework has been significantly improved in three ways.

- The FLR routines have been significantly speeded up with the addition of new auto-differentiation routines, leading to increases in speed between 10 and 15 times. Typically a scenario of 30 projection years and 100 iterations can now be run in 20 – 30 minutes rather than 5 – 8 hours.
- The implementation of the Harvest Control Rules (HCR) has been simplified so that it is now relatively straight forward to implement the structure and intent of each HCR within the FLR framework.
- The implementation of the Management Strategy Evaluation has also been simplified so that alternative scenarios can be set up and run much more efficiently and with less likelihood for error.

These three improvements means that exploration of alternative configurations and possibilities within the Management Strategy Evaluation is now feasible in a workshop environment. Despite these improvements, conducting a MSE in a week long workshop environment remains an extremely challenging task.

5.2. Operating Model

As in the previous workshop, two simulated populations were generated based upon cod and herring as these represent two species with markedly different life histories (Table 1). The simulated populations are not intended to represent any single stock but rather are used to represent a range of different life history characteristics at different levels of exploitation to provide for more extensive testing of the TAC decision rules. The Her-oid and Cod-oid simulated populations capture a range of life-history characteristics, nevertheless there are many stocks that are not covered by this work. Future work may wish to consider long-lived relatively low productivity stocks (such as are found in deep water fisheries – deep-oids) as well as short-lived high productivity stocks (such as squids – short-oids). Finally, there are many invertebrate stocks whose biology is sufficiently different that it seems likely that they would need their own particular Harvest Control Rules to aid in their management.

Table 1. Operating Model scenarios. F_{MSY}, the fishing mortality that should give rise to the MSY when the stock is at B_{MSY}, the spawning stock biomass (SSB) that produces the MSY. The cod like Operating Model assumes a Ricker stock-recruit relationship, while the herring like Operating Model assumes Beverton-Holt. Each scenario is composed of the stock species, the productivity (steepness), the current status, the HCR, and the observation error model.

Scenario	***Factor***	***Level***
Cod-oid	Stock	Cod like
Her-oid		Herring like
oid.0.75	Stock Recruitment	Steepness = 0.75
Oid.0.9		Steepness = 0.9
oid #.1	Current status	Well managed, i.e. F<= F_{MSY} & SSB>=B_{MSY}
oid #.2		Overfishing, i.e. F> F_{MSY} but SSB>B_{MSY}
oid #.3		Overfished, i.e. F <= F_{MSY} and SSB<B_{MSY}

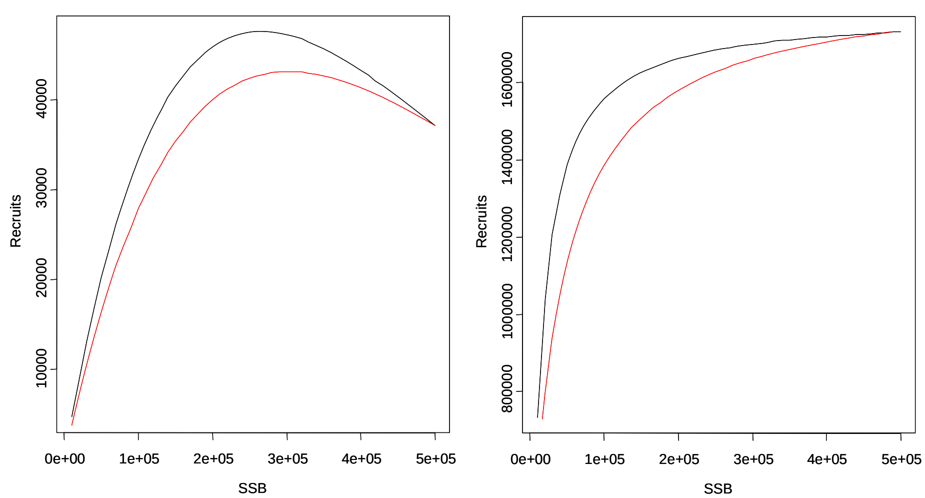

Figure 2. Ricker (left panel) stock recruitment relationship applied to the cod like stocks and Beverton and Holt (right panel) stock and recruitment relationship applied to the herring like stocks. In each case the lower line represents a steepness of 0.75 and the upper line a steepness of 0.9.

5.2.1. Biological Reference Points

In the SGMOS-07-01 report (STECF, 2007b, p12) a method for defining precautionary reference points was specified for when a stock was '*inside safe biological limits*' i.e.

"This was interpreted to be a stock with spawning stock biomass at or above a precautionary reference level (B_{pa}) where B_{pa} is the spawning stock biomass at equilibrium corresponding to a yield which is one half of maximum sustainable yield (MSY). A precautionary fishing mortality (F_{pa}) was then defined as the fishing mortality (taken as a mean over all ages) that gave a yield of 0.5× MSY when the population is at B_{pa}."

This definition potentially confuses the role of the Operating Model (OM) and Management Procedure (MP). The OM models the true stock and characteristic quantities, such as B_{MSY}, F_{MSY} and MSY (all reliant on the true stock-recruit relationship), can be calculated. However, these true MSY related quantities are not available or known to the MP, which reflects the perception of the stock provided by a stock assessment based on data sampled from the OM. Although MSY quantities could be calculated for the perceived stock in the MP, these quantities would rely on an assumption about the stock-recruit relationship, since the true stock-recruit relationship is not known in the MP. For the purposes of this work, the fishing mortality target used in the MP is $F_{0.1}$, a proxy of F_{MSY}, assuming constant recruitment (geometric mean recruitment for the first 30 years of the assessment) for its estimation. $F_{0.1}$ is defined as the value of fishing mortality for which the slope of the yield per recruit curve, as a function of F, is 1/10th of the value at the origin. F_{pa} was then defined as $2\times F_{0.1}$ for the cod-like stock and $3\times F_{0.1}$ for herring the herring-like stock. This was because in the case of the Ricker ("*cod"*) stock recruitment relationship, the slope at the origin is less steep than for the Beverton and Holt (*"herring"*) formulation, and so F_{Crash}[3] occurs at a lower level of fishing mortality. B_{pa} was then defined as the SSB at F_{pa}.

5.2.2. Management Procedures.

The success of a Management Procedure (MP) or management strategy, depends upon the data and stock assessment methods available as well as the management objectives and tools being used. Four management procedures were proposed for evaluation. These were the implicit ICES MP based upon VPA (in fact based upon Extended Survivorship Analysis – XSA), as evaluated in the last meeting which requires significant amounts of information (this selected the maximum of $F_{0.1}$ and F_{sq}, see below), in addition, there was a similar harvest control rule evaluated which differed from the first in that it always selected $F_{0.1}$ (see below). Thirdly, a relatively simple model-free method was proposed for use in relatively data poor circumstances when perhaps only time series of catch and effort data are available. Finally, (to cover off case 9) the same MP as the first VPA approach was used with the addition that a change in selectivity was implemented for immature fish.

The Management Procedures were designed so that they applied to multiple cases (cases as defined in the terms of reference). During the simulations a stock could pass from one status to another so the MPs needed to be flexible and encompass the responses required for all situations. Each MP needed to include a response to the assessment of resource status, it needed to include constraints on the potential TAC changes (dependent upon status), and it needed a stock recovery plan in case the status was below acceptable limits.

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[3] The fishing mortality rate corresponding to an equilibrium spawner-per-recruit (SPR) equal to the inverse of the survival ratio at the origin of the stock-recruitment relationship. A stock exploited indefinitely at this level of F is expected to collapse sooner or later due to recruitment failure

5.2.3. VPA based MP

In the previous meeting a HCR that incorporated i) a target fishing mortality, ii) fishing mortality limits, iii) biomass limits and iv) TAC constraints was developed, i.e.

1) Set target F
   $F_y = \max(F_{sq}, F_{0.1})$
2) Check PA limits
   if $F_y > Fpa$ then set $F_y = F_{pa}$
   Estimate TAC_y
   if $SSB_{y+1} < B_{pa}$ then re-estimate TAC_y so that $SSB_{y+1} = B_{pa}$
3) Check that $(1-\alpha)TAC_{y-1} \leq TAC_y \leq (1+\alpha)TAC_{y-1}$
   if $TAC_y \leq (1-\alpha)TAC_{y-1}$ then $TAC_y = (1-\alpha)TAC_{y-1}$ else
   if $TAC_y \geq (1\dotplus\alpha)TAC_{y-1}$ then $TAC_y = (1\dotplus\alpha)TAC_{y-1}$

4) If $SSB_y < B_{pa}$ and $SSB_{y+1} < SSB_y$ then re-estimate TAC_y so $SSB_{y+1} = SSB_y$
5) If impossible (i.e. $SSB_{y+1} < SSB_y$ even if F=0.0) then set F = 0.01.
6) Check for rise in F
   if $F_y > F_{sq}$ then set $F_y = F_{sq}$ and re-estimate TAC_y

However, it was found that this HCR could generate stock collapse and a major loss of catches under certain conditions (STECF, 2007b). Therefore in this current work we evaluated two alternatives to this rule.

New VPA Based HCR

We define:

y = last data year
y+1 = Assessment Year
y+2 = TAC setting year
α is the limit on the proportional change in TAC permitted.
$F_{sq} = (F_{y-2}+F_{y-1}+F_y)/3$ is the F-status quo

1) Set target F & α
   If $F_y < F_{0.1}$ & $SSB_y > B_{pa}$ then rule 1) $\alpha = 0.25$ & $F_{y+2} = F_{0.1}$
   Else If $F_y \geq F_{0.1}$ & $SSB_y > B_{pa}$ then rule 2) $\alpha = 0.15$ & $F_{y+2} = \max(F_{0.1}, F_{sq})$
   Else if $SSB_y \leq B_{pa}$ then rule 3) $\alpha = 0.20$ & $F_{y+2} = \max(F_{0.1}, 0.7F_{sq})$

2) Check that $(1-\alpha)TAC_{y+1} \leq TAC_{y+2} \leq (1+\alpha)TAC_{y+1}$
   if $TAC_{y+2} < (1-\alpha)TAC_{y+1}$ then $TAC_{y+2} = (1-\alpha)TAC_{y+1}$, else
   if $TAC_{y+2} > (1\dotplus\alpha)TAC_{y+1}$ then $TAC_{y+2} = (1\dotplus\alpha)TAC_{y+1}$

3) If $SSB_{y+2} < B_{pa}$ and $SSB_{y+3} < SSB_{y+2}$ then set $TAC_{y+2} = 0.75*TAC_{y+1}$

where

1) relates to the management response to the assessment,

2) relates to the constraints placed in the potential changes in TAC (different depending on stock status), and

3) relates to the stock recovery plan in the case where the stock in the TAC setting year and the year thereafter is below biological limits.

Second VPA Based HCR

1) Set target F & α

If $F_y < F_{0.1}$ & $SSB_y > B_{pa}$ then rule 1) $\alpha = 0.25$ & $F_{y+2} = F_{0.1}$

Else If $F_y \geq F_{0.1}$ & $SSB_y > B_{pa}$ then rule 2) $\alpha = 0.15$ & $F_{y+2} = F_{0.1}$

Else if $SSB_y \leq B_{pa}$ then rule 3) $\alpha = 0.20$ & $F_{y+2} = \max(F_{0.1}, 0.7F_{sq})$

2) Check that $(1-\alpha)TAC_{y+1} \leq TAC_{y+2} \leq (1+\alpha)TAC_{y+1}$

if $TAC_{y+2} < (1-\alpha)TAC_{y+1}$ then $TAC_{y+2} = (1-\alpha)TAC_{y+1}$, else

if $TAC_{y+2} > (1+\alpha)TAC_{y+1}$ then $TAC_{y+2} = (1+\alpha)TAC_{y+1}$

3) If $SSB_{y+2} < B_{pa}$ and $SSB_{y+3} < SSB_{y+2}$ then set $TAC_{y+2} = 0.75*TAC_{y+1}$

In this case the only difference with the first new HCR is that in the second rule within clause 1) instead of setting $F_{y+2} = \max(F_{0.1},F_{sq})$, the simpler rule of setting $F_{y+2} = F_{0.1}$ is used.

5.2.4. Data Poor HCR

There are limited types of stock assessment model that can be used when only a time series of catch biomass and effort or an index of abundance are available. For example, if both a time series of catch and an index of relative abundance are available it would be possible to use a surplus production or biomass dynamic model to conduct an assessment of stock status. Alternatively, if only an index of abundance is available a model free approach could be used to determine trends in the stock. In the latter case an adaptive management approach could be taken where if the index declines, effort or TAC is reduced until an increase in the index is seen, which, in turn, leads to an increase in effort or TAC.

Punt & Smith (2007?) proposed a rule where an estimate of stock size and or exploitation level is used to set a catch, e.g.

$C = f()$

where f() could be based upon a biomass dynamic model or a model free rule.

This estimate of target catch is then constrained i.e.

if ($C>Q_{Max}$) $TAC_{t+1}=Q_{Max}$

else if ($C<Q_{Min}$) $TAC_{t+1}=Q_{Min}$

else $TAC_{t+1}=C$

based upon upper and lower TAC limits (TAC_{Max} and TAC_{Max} based on observed max and min historical catches) and a TAC constraint α (e.g. 15%)

$Q_{Max} = \min(TAC_{Max}, (1+\alpha)\times TAC_t)$

$Q_{Min} = \max(TAC_{Min}, (1-\alpha)\times TAC_t)$

5.2.5. Model Free

If it is assumed that only a time series of catch and effort are available from the fisheries, i.e. there is no absolute estimate of biomass or of exploitation level, then an adaptive rule can still be applied. For example, if recent CPUE decreases then a TAC is set consistent with an effort decrease.

If $\frac{C_t}{E_t} < U$ then $E_{t+1} = 0.85E_{t+1}$ else $E_{t+1} = \overline{E}_t$

Where U is the 50th percentile of the observed CPUE, $\overline{E}_t$ is the mean effort level over the chosen reference period, and catch next year is set by

$C_{t+1} = UE_t$

Subsequently the catch constraint rule of Punt and Smith is applied.

Similarly, if recent CPUE increases then a TAC is set consistent with an effort increase:

If $\frac{C_t}{E_t} > U$ then $E_{t+1} = 1.15E_{t+1}$ else $E_{t+1} = \overline{E}_t$

Table 2. Management Procedures

Scenario	***Factor***
oid.#.#.1	VPA based – clause 1, rule 2 $F_{y+2} = \mathrm{Max}(F_{0.1},F_{sq})$
oid.#.#.2	VPA based – clause 1, rule 2 $F_{y+2} = F_{0.1}$
oid.#.#.3	VPA Based plus change in Selectivity in the immature fish. clause 1, rule 3 only (used in Case 9 only).
oid.#.#.4	Model Free – based on catch rate changes.

5.3. Observation Error Model

When comparing model free and model based MPs it is important to consider a range of plausible bias and noise to test their robustness to uncertainty. Therefore in the OEM we implement uncertainty due to measurement and model error.

For example often when performing a stock assessment based upon virtual population analysis (VPA) a retrospective pattern will be seen. Looking for such patterns is commonly done by stock assessment working groups, however, determining what causes such patterns is difficult. Retrospective patterns can be caused by changes in population characteristics that are assumed to be stable over time, such as selectivity, catchability, or natural mortality. But they may also be caused by conflicting signals coming from commercial or survey indices. Such biases can be important in affecting the performance of a harvest control rule (HCR) if it is also a function of trends in the data and if the stock assessment attempts to account for it.

Table 3. Observation Error Model scenarios

Scenario	***Factor***	***Level***
oid.#.#.#.1	Measurement Error	30% CV on CPUE assuming log-normal error
oid.#.#.#.2	Retrospective bias	Recent increase in q, chosen to give an x% bias in F

The OMs for each case will be selected from one or more of the options in table 1 – 3, which combines a species type, a steepness, a current status, a Management Procedure (or HCR) and an observation error model. By running different combinations of these components this allows the performance of the MPs to be compared across scenarios. In order to evaluate the performance of the different MPs, summary statistics (listed in table 4) are collected from the OM (i.e. the biological population and the fleet), with time series of values saved for each scenario and iteration.

Table 4. Summary Statistics

Statistic	*Name*	*Description*
SS.1	Revenue	Yield times price.
SS.2	Costs	Fixed costs of fishing.
SS.3	Profits	The difference between revenue and costs.
SS.4	Landings	Reported landings as biomass.
SS.5	Total Catch	Reported landings plus bycatch and discards as biomass.
SS.6	Discards	Amount as biomass caught but not landed.
SS.7	SSB	Spawning Stock Biomass – mature biomass.
SS.8	Biomass	Total legal sized biomass.
SS.9	Mean Size	Average size as length of fish.
SS.10	Proportion Mature Biomass	Literally the proportion of the stock biomass that is mature.
SS.11	Exploitation Rate	Annual Catch divided by Total Legal sized Biomass.

6. Cases

Cases 1), 2), 3), and 4) all assume a VPA based MP where both catch and CPUE-at-age are available. In those cases where "*the status of the stock is not known precisely" i.e.* cases 5), 6), 7) & 8), it is assumed that this is because of the quality of the data available[4] and that the management procedure is based solely upon a time series of CPUE (that is a model free procedure would be used). For case 9) it is assumed that historical and future catch-at-age and indices of abundance are available and so the MP will be the same as in case 4) but in addition, effort reductions and mesh changes will be implemented (effectively changing the selectivity of immature fish). For case 10) it is assumed that both an historical catch and effort time series are available.

There are two elements to a management plan i.e. a long-term strategy and a recovery plan. However, at the start of a simulation it will not necessarily be known if a stock is in a "well managed" or "overfished" state or is subject to "overfishing". In addition, during a simulation a stock could move between states as the forward simulations progress. Therefore, as at the two previous STECF HCR meetings (STECF 2007a, b) it was decided that a generic HCR should contain both long-term and recovery elements. Therefore, even when the stock is initially at a long-term target the relevant management plan will include a recovery element and vice versa.

[4] Other causes could be due to either i) a new fishery or ii) a stock assessment has not been conducted. In the case of i) the stock status would be at virgin biomass and ii) would become one of cases 1), 2) and 3) after the first assessment was conducted.

Similarly for the reasons outlined above, cases 5), 6), 7) and 8) should be evaluated using the same model free rule, since it is expected that as a rule is applied the trend in a stock will change and even if a stock is overexploited it can increase due to strong year-classes.

Table 4. Management Strategy Evaluation options

	Scientific advice	Action to take in setting TAC	OM	MP	OEM
1)	Stock exploited consistently with maximum sustainable yield.	Aim to set the TAC to the forecast catch corresponding to the fishing mortality that will deliver the highest yield in the long term[1], **but** do not change the TAC by more than 25%.	OM.1.1 Cod like OM.1.2 Herring like OM.2.1 Steepness = 0.75 OM.2.2 Steepness = 0.9 OM3.1 $F<= F_{MSY}$ & $SSB>=B_{MSY}$	1) Set target F $F_y=F_{0.1}$ 2) Check that $(1-\alpha^{5})TAC_{y-1} \leq TAC_y \leq (1+\alpha)TAC_{y-1}$ if $TAC_y \leq (1-\alpha)TAC_{y-1}$ then $TAC_y = (1-\alpha)TAC_{y-1}$ else if $TAC_y \geq (1+\alpha)TAC_{y-1}$ then $TAC_y = (1+\alpha)TAC_{y-1}$ 3) If $SSB_y < B_{pa}$ and $SSB_{y+1} < SSB_y$ then re-estimate TAC_y so $SSB_{y+1} = SSB_y$ 4) If impossible (i.e. $SSB_{y+1} < SSB_y$ even if F=0.0) then set F = 0.01.	**OE.1.1** 30% CV on CPUE
2)	Stock overexploited compared to maximum sustainable yield but inside safe biological limits.	Aim to set the TAC to the higher value of (a) to the forecast catch corresponding to taking the highest yield in the long term[1] or (b) continuing to fish at an unchanged mortality rate, **but** do not change the TAC by more than 15%.	OM.1.1 Cod like OM.1.2 Herring like OM.2.1 Steepness = 0.75 OM.2.2 Steepness = 0.9 OM 3.2 $F> F_{MSY}$ & $SSB>B_{PA}$	1) Set target F $F_y=\max(F_{sq},F_{0.1})$ 2) Check that $(1-\alpha^{6})TAC_{y-1} \leq TAC_y \leq (1+\alpha)TAC_{y-1}$ if $TAC_y \leq (1-\alpha)TAC_{y-1}$ then $TAC_y = (1-\alpha)TAC_{y-1}$ else if $TAC_y \geq (1+\alpha)TAC_{y-1}$ then $TAC_y = (1+\alpha)TAC_{y-1}$ 3) If $SSB_y < B_{pa}$ and $SSB_{y+1} < SSB_y$ then re-estimate TAC_y so $SSB_{y+1} = SSB_y$ 4) If impossible (i.e. $SSB_{y+1} < SSB_y$ even if F=0.0) then set F = 0.01.	**OE.1.1** 30% CV on CPUE
3)	Stock outside safe biological limits	Aim to set the TAC to the forecast catch that will result in a 30% reduction in fishing mortality rate, **but** do not decrease the fishing mortality so far as to prejudice long-term yields **and** do not	OM.1.1 Cod like OM.1.2 Herring like OM.2.1 Steepness = 0.75 OM.2.2 Steepness = 0.9 OM 3.3 $F> F_{MSY}$ & $SSB<B_{PA}$	1) Set target F $F_y=\max(0.70F_{sq},F_{0.1})$ 2) Check that $(1-\alpha^{7})TAC_{y-1} \leq TAC_y$ if $TAC_y \leq (1-\alpha)TAC_{y-1}$ then $TAC_y = (1-\alpha)TAC_{y-1}$ else 3) If $SSB_y < B_{pa}$ and $SSB_{y+1} < SSB_y$ then re-estimate TAC_y so $SSB_{y+1} = SSB_y$ 4) If impossible (i.e. $SSB_{y+1} < SSB_y$ even if F=0.0) then set F = 0.01.	**OE.1.1** 30% CV on CPUE

[5] $\alpha = 25\%$
[6] $\alpha = 15\%$

	Scientific advice	Action to take in setting TAC	OM	MP	OEM
		reduce the TAC by more than 20%.			
~~4)~~ If impossible (i.e. SSBy+1 < SSBy even if F= 0.0) then set F = 0.01	Stock is subject to long-term plan and scientists advise on the catch that corresponds to the plan.	The TAC must be set by following the relevant plan.	OM.1.1 Cod like OM.1.2 Herring like OM.2.1 Steepness = 0.75 OM.2.2 Steepness = 0.9 OM 3.1 F<= FMSY & SSB>BMSY OM 3.2 F> FMSY & SSB>BPA OM 3.3 F> FMSY & SSB<BPA	1) Set target F Fy=F0.1 2) Check that (1- α)TACy-1 □ TACy □ (1+ α)TACy-1 if TACy ≤ (1- α)TACy -1 then TACy = (1- α)TACy-1 else if TACy ≥ (1+ α)TACy-1 then TACy = (1+ α)TACy-1 3) If SSBy < Bpa and SSBy+1 < SSBy then re-estimate TACy so SSBy+1 = SSBy	**OE.1.1** 30% CV on CPUE
5)	State of the stock not known precisely and STECF advises on an appropriate catch level.	Aim to set the TAC according to STECF advice **but** do not change the TAC by more than 15%.	OM.1.1 Cod like OM.1.2 Herring like OM.2.1 Steepness = 0.75 OM.2.2 Steepness = 0.9 OM 3.1 F< FMSY & SSB>BMSY OM 3.2 F> FMSY &	Rule of Punt and Smith	**OE.1.1** 30% CV on CPUE

[7] α = 20%

	Scientific advice	Action to take in setting TAC	OM	MP	OEM
			SSB>BPA OM 3.3 F> FMSY & SSB<BPA		
6)	State of the stock not known precisely and STECF advises to reduce fishing effort.	The TAC should be reduced by up to 15% and STECF should be asked to advise on the appropriate level of effort.	OM.1.1 Cod like OM.1.2 Herring like OM.2.1 Steepness = 0.75 OM.2.2 Steepness = 0.9 OM3.1 F<= FMSY & SSB>BMSY OM 3.2 F> FMSY & SSB>BPA OM 3.3 F> FMSY & SSB<BPA	Rule of Punt and Smith	**OE.1.1** 30% CV on CPUE
7)	State of the stock not known precisely and STECF advises the stock is increasing	The TAC should be increased by up to 15%.	OM.1.1 Cod like OM.1.2 Herring like OM.2.1 Steepness = 0.75 OM.2.2 Steepness = 0.9 OM3.1 F<= FMSY & SSB>BMSY OM 3.2 F> FMSY & SSB<BPA OM 3.3 F> FMSY & SSB>BPA	Rule of Punt and Smith	**OE.1.1** 30% CV on CPUE
8)	State of the stock not known precisely and STECF advises the stock is decreasing	The TAC should be decreased by up to 15%.	OM.1.1 Cod like OM.1.2 Herring like OM.2.1 Steepness = 0.75 OM.2.2 Steepness = 0.9 OM3.1 F<= FMSY & SSB>=BMSY OM 3.2 F> FMSY & SSB<BPA OM 3.3 F> FMSY & SSB>BPA	Rule of Punt and Smith	**OE.1.1** 30% CV on CPUE
9)	STECF advises a zero catch, a reduction to the	The TAC should be reduced by 25%. Recovery measures	OM.1.1 Cod like OM.1.2 Herring like OM.2.1 Steepness = 0.75	i) As 4) above but with 2 additional scenarios corresponding to ii) a change in mesh corresponding to 50% decreases in	**OE.1.1** 30% CV on CPUE

	Scientific advice	Action to take in setting TAC	OM	MP	OEM
	lowest possible level or similar advice.	should be implemented including effort reductions and introduction of more selective fishing gear as appropriate.	OM.2.2 Steepness = 0.9 OM 3.3 F> FMSY & SSB<BPA	selectivity of immature fish. iii) As 4) but effort capacity halved.	
10)	There is no STECF advice.	While advice is being developed, TACs should be adjusted towards recent real catch levels but should not be changed by more than 15% per year **or** relevant Member States should develop an implementation plan to allow advice to be provided within a short time-frame.	OM.1.1 Cod like OM.1.2 Herring like OM.2.1 Steepness = 0.75 OM.2.2 Steepness = 0.9 OM3.1 F<= FMSY & SSB>=BMSY OM 3.2 F> FMSY & SSB>BPA OM 3.3 F> FMSY & SSB<BPA	Rule of Punt and Smith but with a model free rule	**OE.1.1** 30% CV on CPUE

7. CONDITIONING

Historic time series were generated for 100 years where initially the stock (codoid or heroid) was at equilibrium corresponding to the assumed stock-recruitment relationship (Ricker for codoid and Beverton and Holt for heroid, each with steepnesses of 0.75 and 0.9) and the fishing mortality regime (=F_{MSY}, >F_{MSY}) and recent recruitment level (no change, reduction). Thus, no change to recruitment and conditioning at F_{MSY} gave rise to initial conditions representing a well managed stock (status 1). No change to recruitment and fishing at greater than F_{MSY} gave rise to a stock that had experienced overfishing (status 2). Finally, A reduction in recruitment levels combined with fishing at F_{MSY} gave rise to a stock that was overfished (status 3). The only uncertainty was in the assumed recruitment around the stock recruitment relationship. Examples are shown for a selected OM, plots for all OMs are given in the appendix.

Expected stock dynamics are summarised using an age-structured equilibrium model (in figure 3) that combined SSB-per-recruit, yield-per-recruit and stock/recruitment analyses, using partial fishing mortality- (Fa), natural mortality- (Ma) and mass-at-age (Wa) data, with a stock/recruitment relationship. The spawning stock biomass per recruit (SSB/R) is given by:

$$SSB/R = \sum_{a=r}^{n-1} e^{-\sum_{i=r}^{a-1}(F_i+M_i)} W_a Q_a + e^{-\sum_{i=r}^{n-1}(F_i+M_i)} \frac{W_n Q_n}{1-e^{-F_n-M_n}} \qquad (1)$$

where the 2nd term is the plus-group (i.e. summation of all ages from the last age to infinity). Likewise for yield per recruit (Y/R), if all individuals die at age n, then:

$$Y/R = \sum_{a=r}^{n-1} e^{-\sum_{i=r}^{a-1}(F_i+M_i)} W_a \frac{F_a}{F_a+M_a}(1-e^{-F_a-M_a}) + e^{-\sum_{i=r}^{n-1}(F_i+M_i)} W_n \frac{F_n}{F_n+M_n} \qquad (2)$$

where a is the age, n the plusgroup age, r the age at recruitment, Wa the mass-at-age in the catch, and Qa the proportion mature-at-age.

By rearranging the stock/recruitment model parameters, recruitment can be expressed as a function of SSB/R. For a Ricker stock recruitment relationship

$$R = \frac{\ln[\alpha(SSB/R)]}{\beta(SSB/R)} \qquad (3)$$

and Beverton and Holt

$$R = \alpha - \frac{\beta}{SSB/R} \qquad (4)$$

The spawning stock biomass can then be found as a function of F from the product of equations (1) and (3), while yield is calculated from by the product of equations (2) and (3).

Figure 3 Shows the equilibrium (i.e. expected) dynamics for the herring and cod like stock with steepnesses of 0.75 and 0.9 (oid.0.75 and oid.0.9 respectively) and where currently the stock is well managed (oid.#.1). Figure 4 shows the corresponding time series and figure 5 shows the initial yield, F and SSB, scaled by the corresponding MSY values, with respect to the expected dynamics. These are given as an example of how to interpret the OMs.

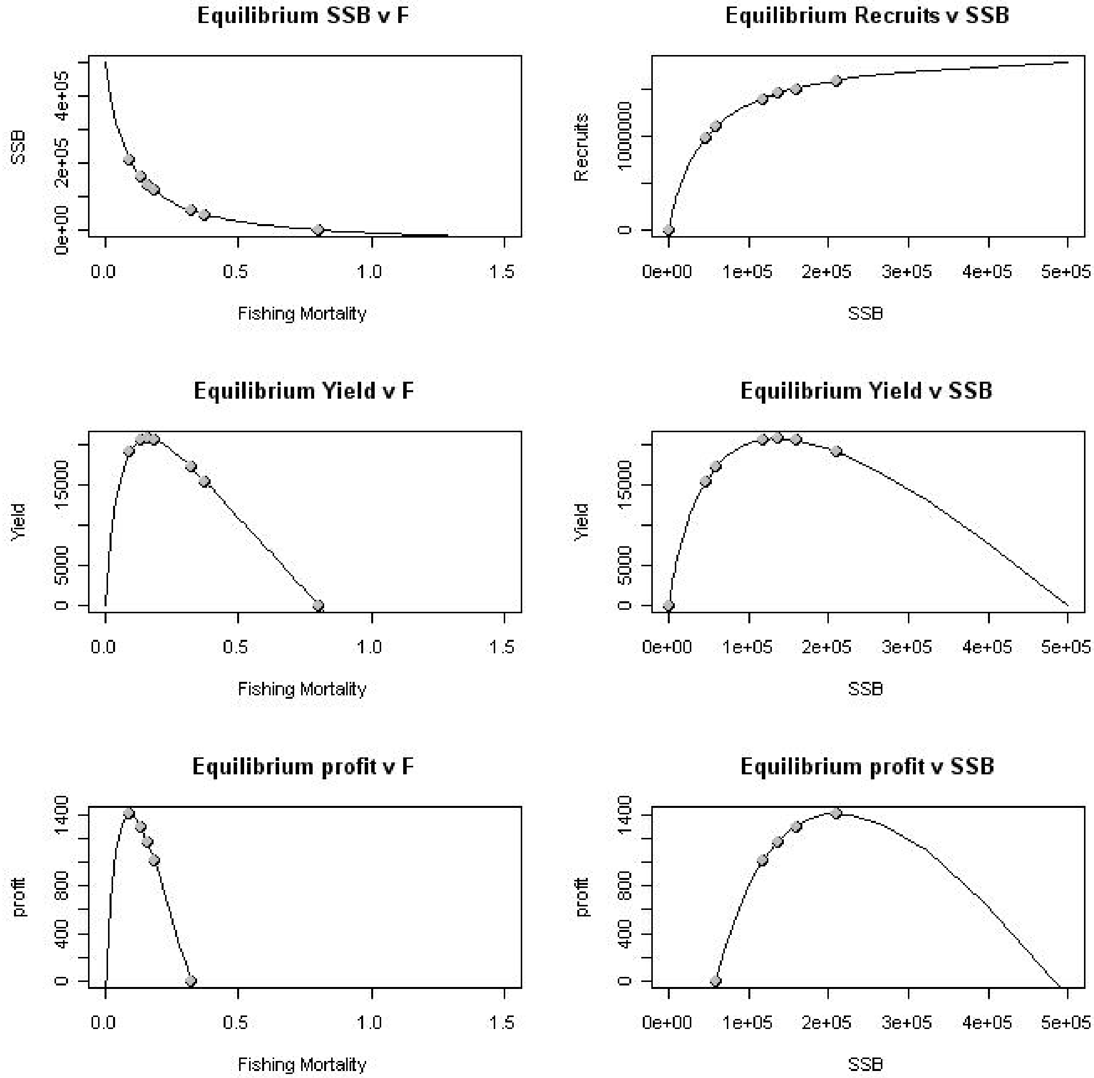

Figure 3a. Herring like with steepness=0.75; expected dynamics as predicted from the equilibrium curves, points on the curve correspond to the reference points 30%SPR0, $F_{0.1}$, F_{Max}, F_{MSY}, F_{MEY} and the breakeven point.

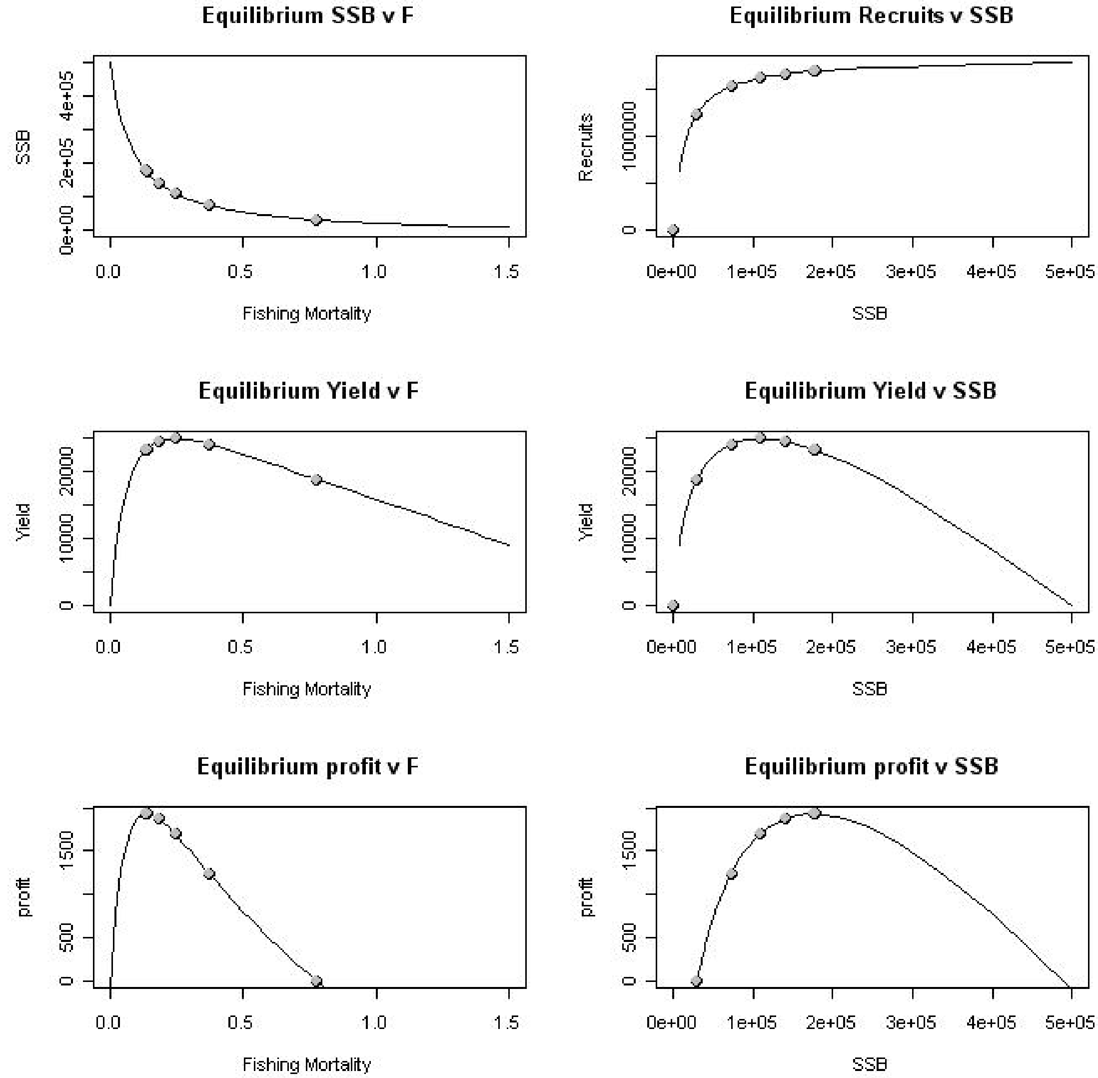

Figure 3b. Herring like with steepness=0.9; expected dynamics as predicted from the equilibrium curves, points on the curve correspond to the reference points 30%SPR0, $F_{0.1}$, F_{Max}, F_{MSY}, F_{MEY} and the breakeven point.

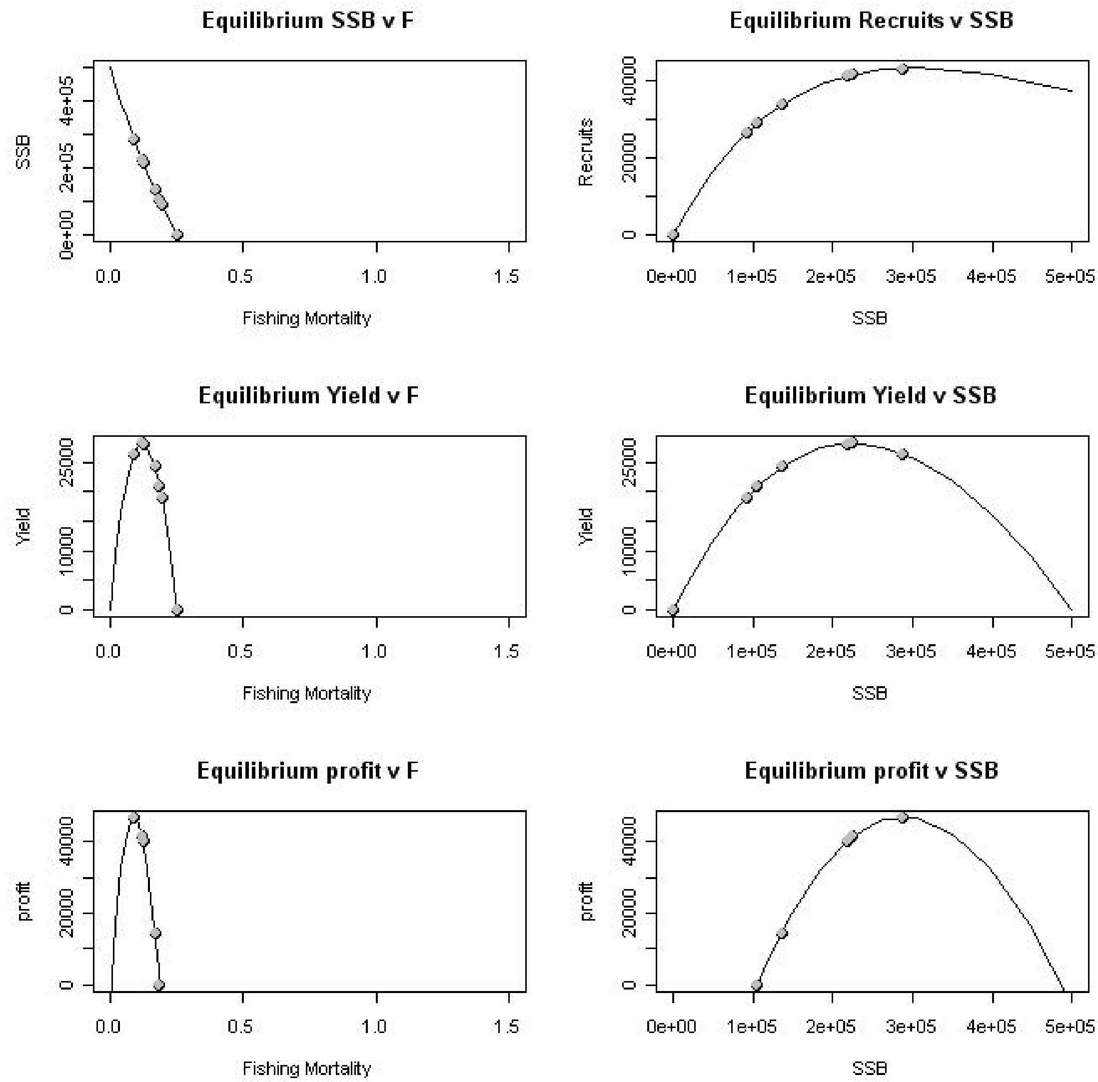

Figure 3c. Cod like with steepness=0.75; expected dynamics as predicted from the equilibrium curves, points on the curve correspond to the reference points 30%SPR0, $F_{0.1}$, F_{Max}, F_{MSY}, F_{MEY} and the breakeven point.

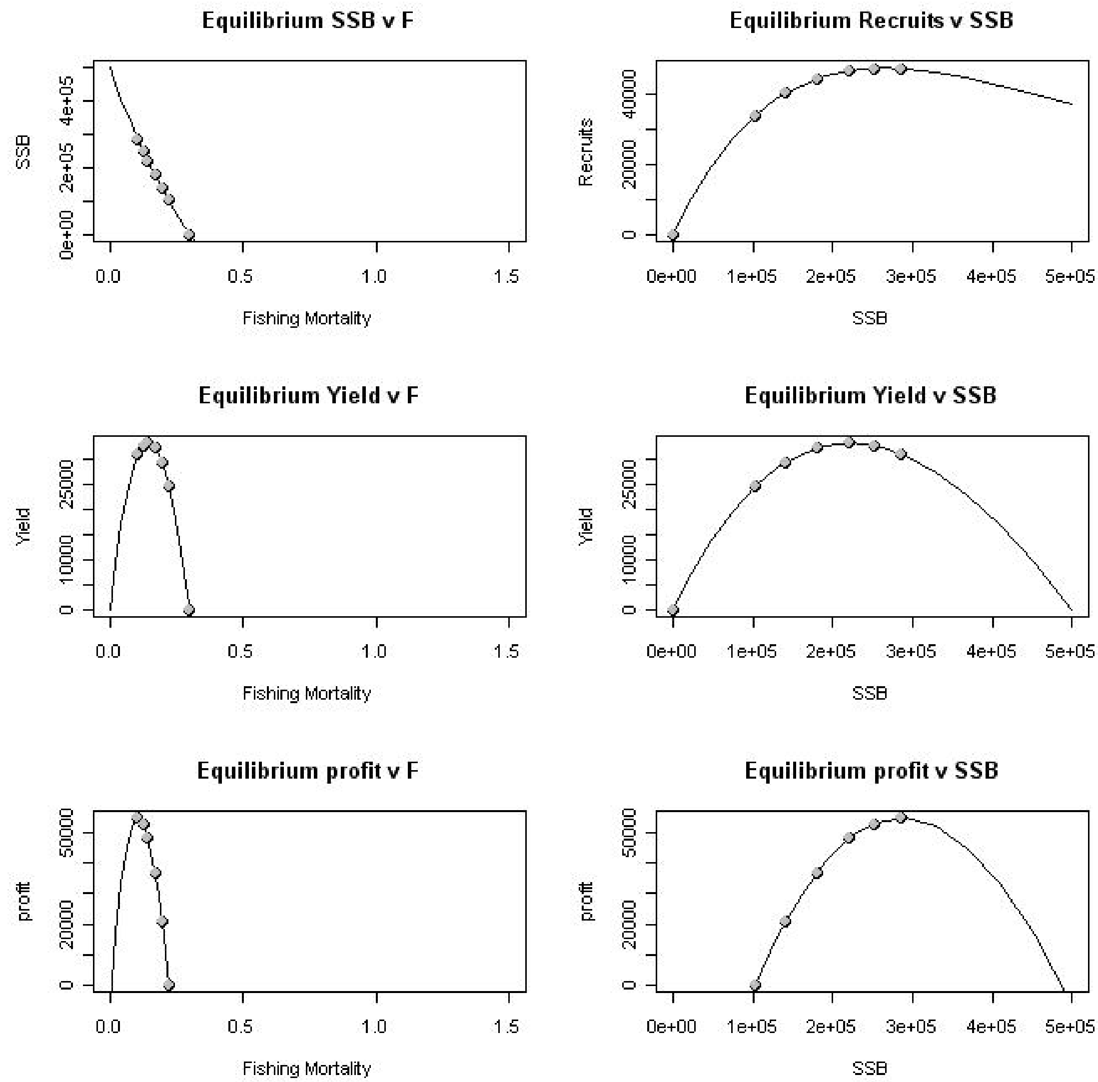

Figure 3d. Cod like with steepness=0.9; expected dynamics as predicted from the equilibrium curves, points on the curve correspond to the reference points 30%SPR0, $F_{0.1}$, F_{Max}, F_{MSY}, F_{MEY} and the breakeven point.

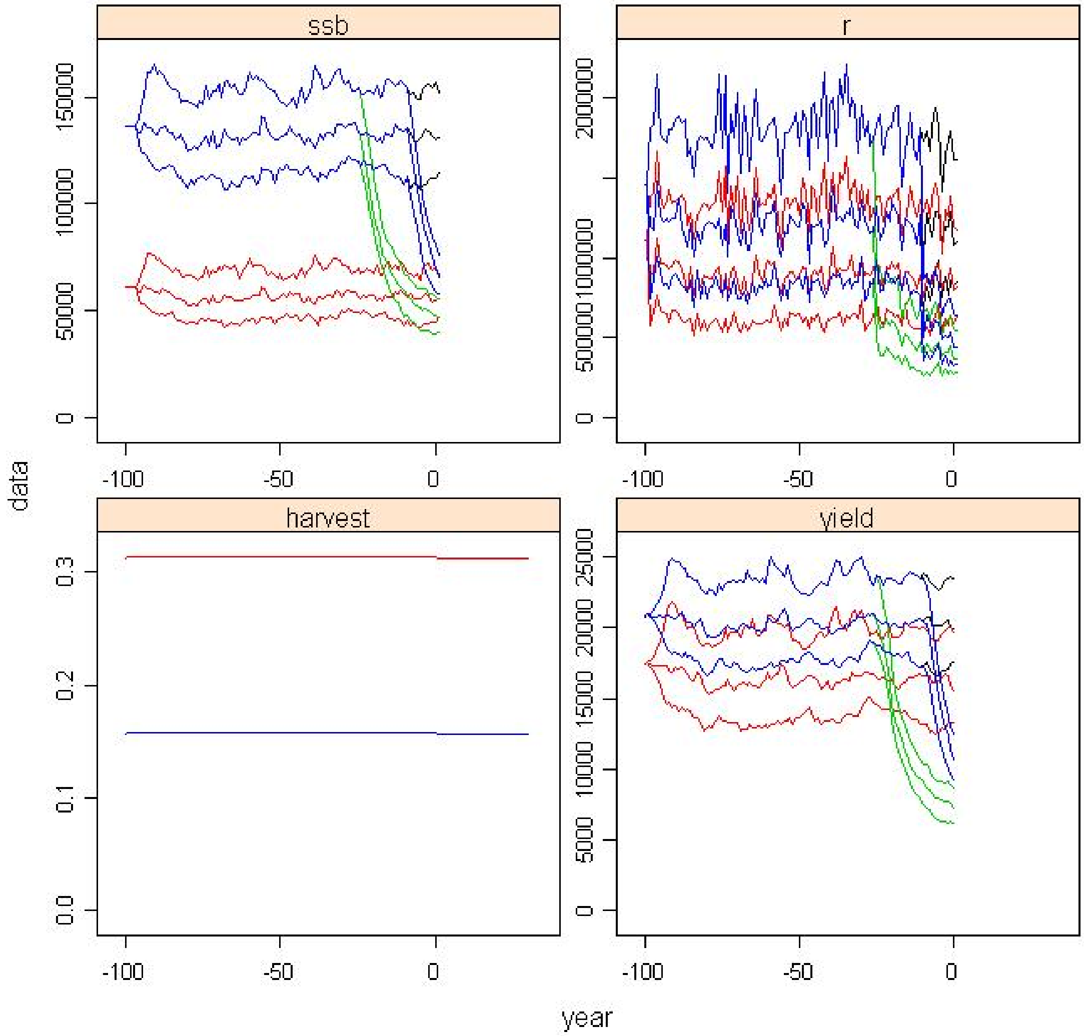

Figure 4a. Herring, steepness=0.75; historic time series showing the median and inter-quartile ranges for the four different initial stock status conditions. Only well managed, overfishing, amd overfished conditions are used in the simulations.

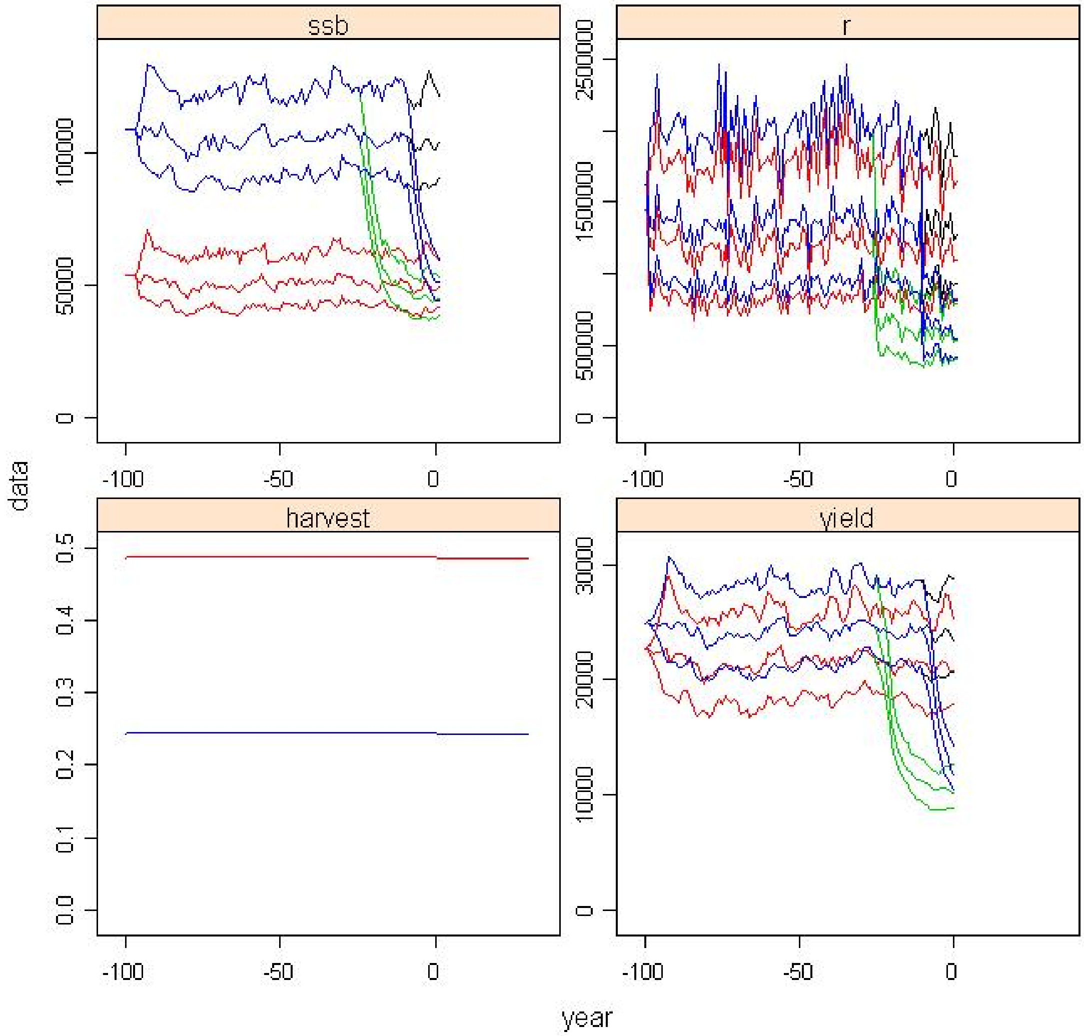

Figure 4b. Herring, steepness=0.9; historic time series showing the median and inter-quartile ranges for the four different initial stock status conditions.

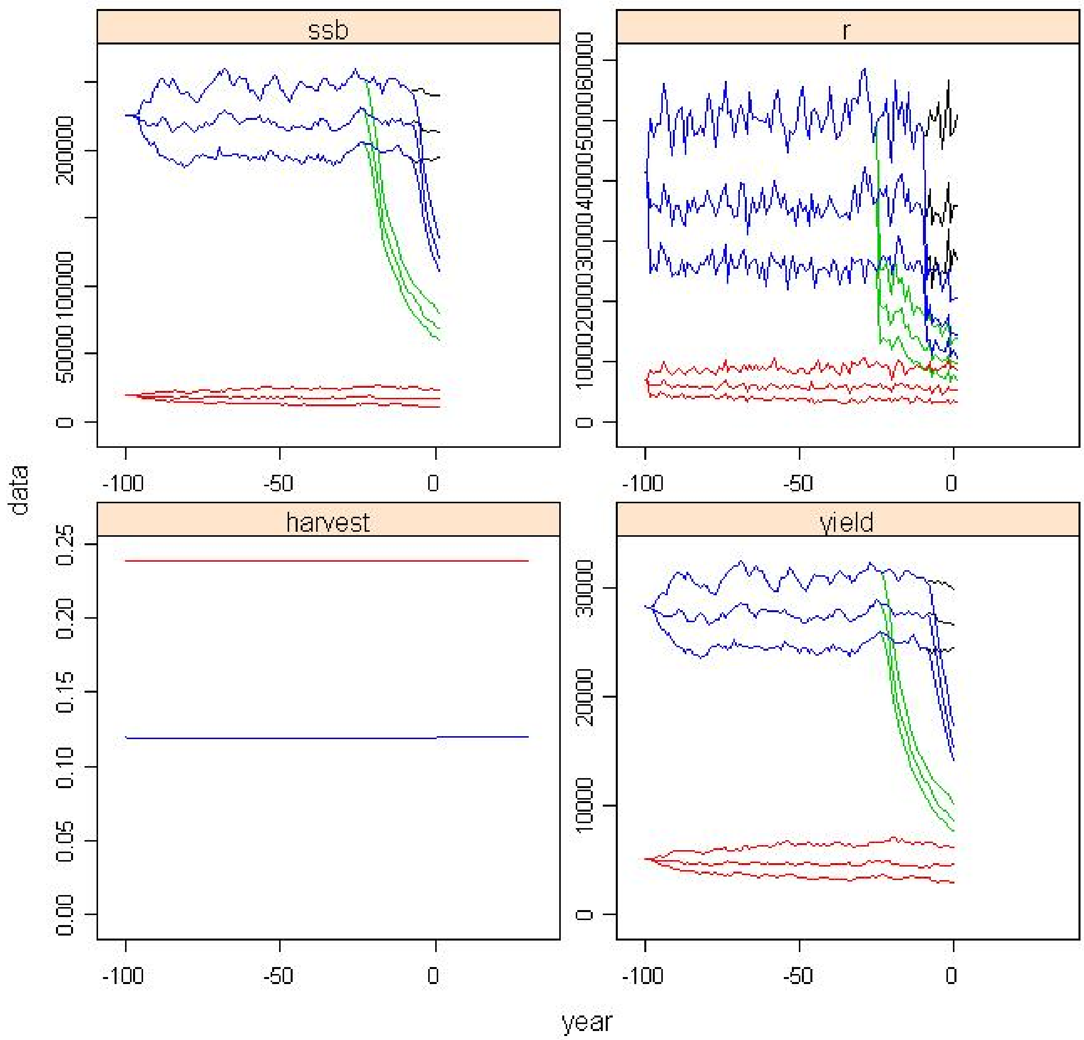

Figure 4c. Cod, steepness=0.75; historic time series showing the median and inter-quartile ranges for the four different initial stock status conditions.

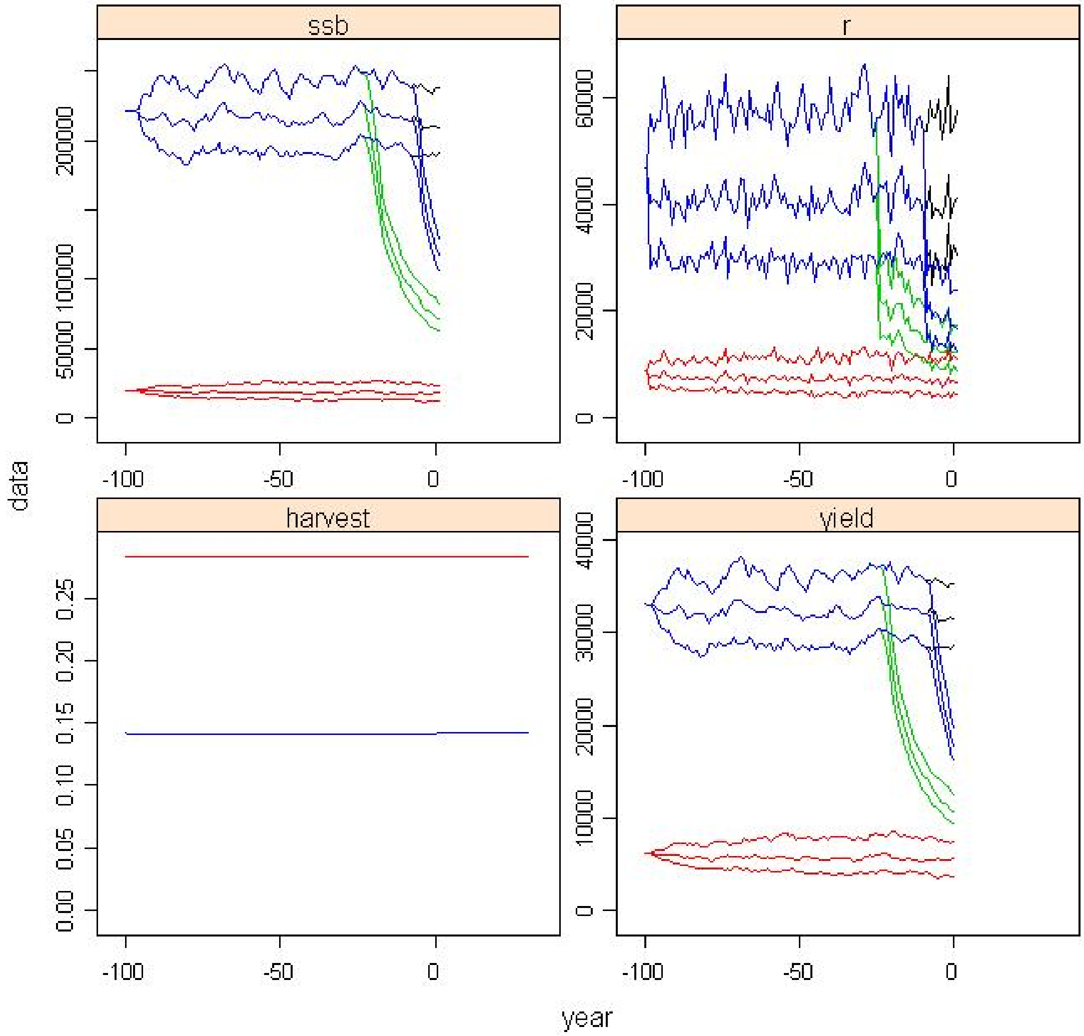

Figure 4d. Cod, steepness=0.9; historic time series showing the median and inter-quartile ranges for the four different initial stock status conditions.

In figure 5 the relationship between yield and SSB and fishing mortality and SSB are shown. The red zone corresponds to the stock being overfished ($SSB<B_{MSY}$) and overfishing occurring ($F>F_{MSY}$), while the green zone to the stock being $>B_{MSY}$ and fishing being $<F_{MSY.}$ The dots correspond to 100 realisations in year=0 for the options corresponding to current status shown in Figure 4.

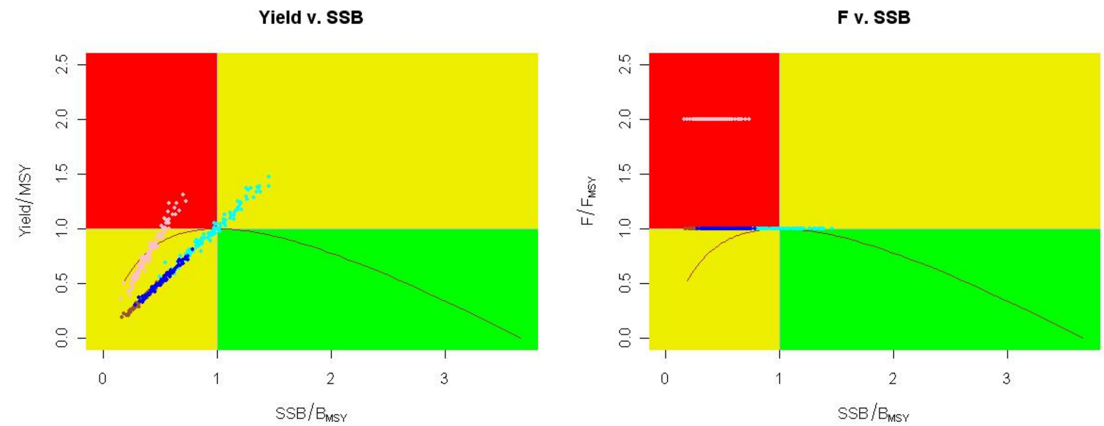

Figure 5a. Herring, steepness=0.75; starting conditions with respect to MSY, F_{MSY} and B_{MSY}

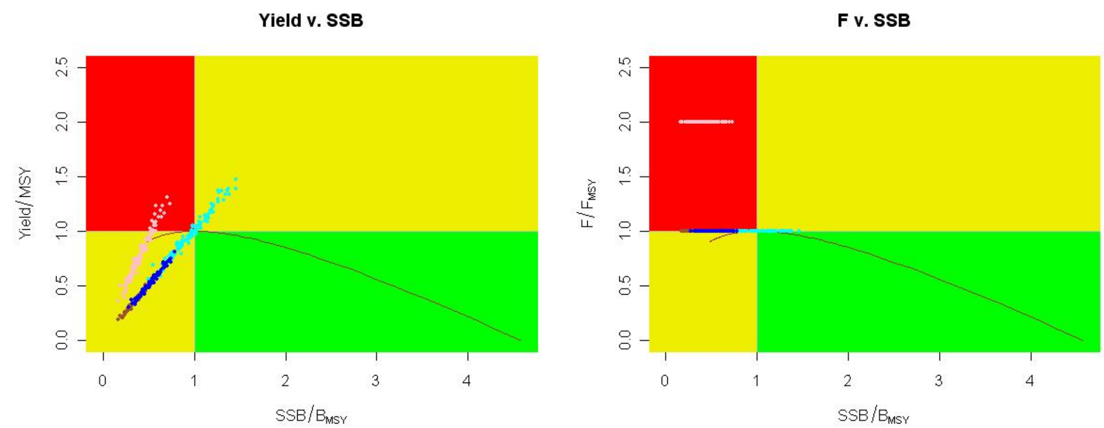

Figure 5b. Herring, steepness=0.9; starting conditions with respect to MSY, F_{MSY} and B_{MSY}

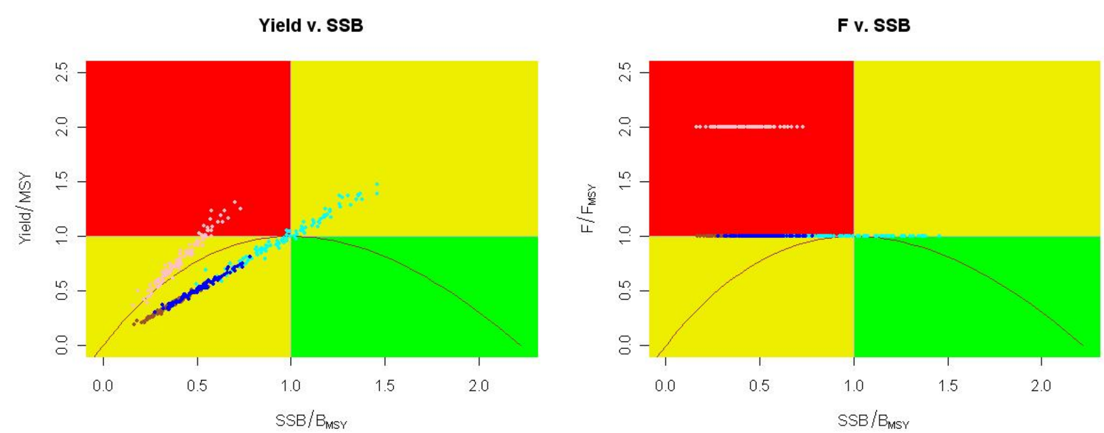

Figure 5c. Cod, steepness=0.75; starting conditions with respect to MSY, F_{MSY} and B_{MSY}

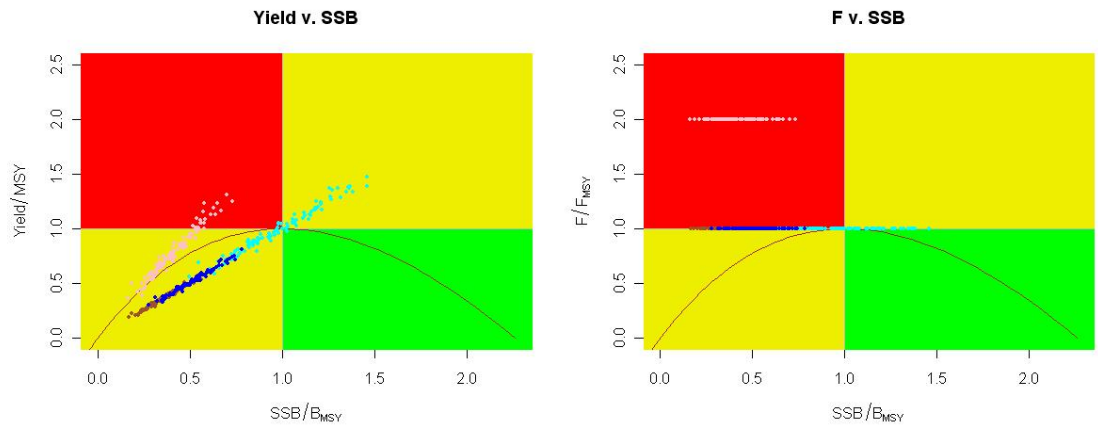

Figure 5d. Cod, steepness=0.9; starting conditions with respect to MSY, F_{MSY} and B_{MSY}

1. <u>**FLR**</u>

HCRs can be modelled using the `fwd` method found in the FLash package (see http://flr-project.org/doku.php?id=documentation:tutorials:hcr).

For example, for the HCR of case 1 (Stock exploited consistently with maximum sustainable yield.)

1) Set target F
   $F_y=F_{0.1}$
2) Check that $(1-\alpha)TAC_{y-1} \leq TAC_y \leq (1+\alpha)TAC_{y-1}$
   if $TAC_y \leq (1-\alpha)TAC_{y-1}$ then $TAC_y = (1-\alpha)TAC_{y-1}$ else
   if $TAC_y \geq (1+\alpha)TAC_{y-1}$ then $TAC_y = (1+\alpha)TAC_{y-1}$
3) If $SSB_y < B_{pa}$ and $SSB_{y+1} < SSB_y$ then
   re-estimate TAC_y so $SSB_{y+1} = SSB_y$
4) If impossible (i.e. $SSB_{y+1} < SSB_y$ even if F=0.0) then
   set F = 0.01.

Steps 1) and 2) comprise a long-term strategy, while steps 3) and 4) comprise a recovery plan if the stock falls below B_{pa}.

`fwd()` takes as arguments an FLStock object and a data frame of type `fwdTarget` with columns representing the various targets and limits. The long-term strategy can be modelled by the `fwdTarget` data frame e.g.

```
  year     value      min      max quantity   rel
1   30 0.3482114       NA       NA      "f"    NA
2   31 0.1059053       NA       NA      "f"    NA
3   31        NA     0.85     1.15 "catch"    30
```

and the recovery plan by

```
   year value min max quantity rel
1   30    NA    1  NA     "ssb"  29
2   30    NA 0.01  NA       "f"   NA
```

"year" specifies the target year and "value" the actual target value, while "quantity" specifies the type of target (e.g. F, SSB etc.). "min" and "max" allow bounds on the target to be specified, whilst "rel" allows the target to be set relative to a reference year.

8. RESULTS

During the workshop 34 different scenarios were considered in detail but insufficient time remained to generate the remaining possible scenario combinations. There were 20 scenarios explored for the codoid stocks and 14 heroid stock combinations considered (Table 5). These groupings still provided sufficient contrasts to provide information concerning how the different Management Procedures or Harvest Control Rules operated under different conditions. The stocks were identified through their labels, for example cod.0.75.1.1.1: where cod or her denoted codoid or heroid. The value 0.75 or 0.9 following the species denoted the steepness of the stock recruitment relationship (where the codoid assumed the Beverton-Holt relationship while the heroid assumed the Ricker stock recruitment relationship. Then the first 1 denoted the initial conditions of the stock (1 well managed, 2 overfishing and 3 being overfished). The second 1 denotes the management procedure or HCR used, while the final 1 denoted the Observation Error Model used.

8.1. Model Free HCR

The model free Harvest Control Rule (MP 4) was quickly found to be dysfunctional (*e.g.* cod.0.9.1.4.1; Fig 6d). Its effect was to increase fishing mortality leading to an initial increase in yields but this was quickly followed by accelerated increases in fishing mortality, reductions in SSB, yield, revenue and eventual stock collapse. The particular arrangement used in the model free HCR was clearly unsuccessful and alternatives are required. Insufficient time was available to explore alternative arrangements. However, the use of a constant multiplier on fishing effort (and hence fishing mortality) was obviously not sufficiently adapted to changes in observed CPUE levels. Implementing a variable deltaE to prevent run-away increases in fishing mortality may correct that failure and provide time for the CPUE to change and the HCR to adapt to changing conditions within the fishery.

8.2. VPA HCR (Max of $F_{0.1}$,F_{sq})

The first variant on the VPA based harvest control rule had, as the response to the assessment the setting of fishing mortality to the maximum of either $F_{0.1}$ or F_{sq}. This HCR performed better than the HCR developed in the previous STECF HCR meeting (STECF, 2007a, b), but it continued with some problems. The key response to the assessment, of selecting the maximum of $F_{0.1}$ or F_{sq} had the effect of ratcheting the fishing mortality upwards wherever variation permitted this.

With some well managed stocks (cod.0.9.1.1.1, her.0.75.1.1.1; Figs 6a, 7a) fishing mortality rose slightly. This had only minor effects with the herring like stock but increased the variation of the responses in the cod like stock and even for the relatively high productivity stock (steepness = 0.9) occasional runs led to fishery collapses. Conversely with the herring like stock and a steepness of 0.9 (her.0.9.1.1.1 and Fig 9a) there was a slight decline in fishing mortality. With well managed stocks the impacts of this HCR were minor.

With stocks that were experiencing overfishing there were variable results (cod.0.75.2.1.1, her.0.75.2.1.1 and her.0.9.2.1.1; Figs 7d, 8d, and 9c). The cod like species with a steepness of 0.75 exhibited an increase in variation but no recovery in SSB and the fishery remained mostly generating negative profits. In short, variation increased in most statistics but there was no improvement in yields, revenue, profits, or SSB. The herring like species with a steepness of 0.75 exhibited a small and slow decrease in fishing mortality which was reflected by a small and slow increase in SSB and profits, but yields effectively did not change.

However, the herring like species with a steepness of 0.9 was different. It exhibited a rapid decline in fishing mortality which led to significant recovery of the SSB starting after about 5 years. Profits began to rise after about 8 years, yields were initially down but returned to their starting levels by the end of the thirty years.

With stocks that were overfished (cod.0.75.3.1.1, cod.0.9.3.1.1, and her.0.75.3.1.1; Figs 6e, 7e, 8e) this harvest control rule had variable results. With the low productivity cod like stock (steepness = 0.75) fishing mortality declined slightly leading to significant recovery. However, at the same time the variation in the output statistics increased so that some instances led to fishery collapse. With the higher productivity cod like stock (steepness = 0.9) the recovery in recruitment led to a greater decline in fishing mortality leading to greater stock recovery in the same time as well as increased yields and increased profits. However, there were still some runs which led to fishery collapse. Finally the low productivity herring like stock (steepness = 0.75) responded to this HCR by a rapid decline in fishing mortality leading to a recovery of the SSB, and of yield and of profits.

In summary for this HCR, well managed stocks tended to become slightly more variable with some slight declines in the cod like species and slight increases in the herring like species. In stocks experiencing overfishing, low productivity stocks only recovered weakly if at all, while more productive stocks experiencing overfishing exhibited significant rebuilding and recovery. Overfished stocks generally all exhibited at least some degree of recovery, and good recovery in some cases. Not surprisingly, more productive stocks recovered more rapidly than lower productivity stocks.

8.3. VPA HCR (Max of $F_{0.1}$,F_{sq} plus change in selectivity for immature fish)

A variation on the first HCR was considered to deal with Case 9 (which included the provision: "Recovery measures should be implemented including effort reductions and introduction of more selective fishing gear as appropriate."). This was implemented as a reduction in the selectivity of the fishing gear for immature fish.

In all cases with well managed fisheries (cod.0.9.1.3.1, cod.0.75.1.3.1, her.0.9.1.3.1 and her.0.75.1.3.1) the effect of the change to the selectivity imposed on immature fish was to temper or reduce the impact of the management procedure (if there was one).

With stocks experiencing overfishing (cod.0.9.2.3.1, cod.0.75.2.3.1, her.0.9.2.3.1, and her.0.75.2.3.1) there was a difference between the cod like and herring like stocks. The cod like stocks showed similar trends to he unmodified HCR but generally less variation than without the change in selectivity. The herring like stocks showed the same trends as those of the HCR without the selectivity change but the impact was to reduce the extent of the management impact. The extent of stock recovery sometimes appeared slightly lower, although this may have been related to a reduction in variation and more replicate runs may have altered this impression.

Finally. with those stocks that were overfished (cod.0.9.3.3.1, cod.0.75.3.3.1, her.0.9.3.3.1, and her.0.75.3.3.1) the impact of the HCR on both the cod like and herring like stocks was to make the management impacts less variable and less abrupt. The degree of rebuilding, if any, appeared to remain approximately the same but there was less noise in the trajectories.

8.4. VPA HCR ($F_{0.1}$ target)

The second harvest control rule is slightly simpler than the first VPA based rule and was suggested by the observation that the first rule could lead to fisheries being trapped at relatively high fishing mortality rates just because they constituted the status quo. The modification simply removed the selection of the maximum of $F_{0.1}$ and F_{sq}, replacing that with a continual target of $F_{0.1}$.

For well managed fisheries (cod.0.9.1.2.1, cod.0.9.1.2.2, cod.0.75.1.2.1, cod.0.75.1.2.2, her.0.75.1.2.1, her.0.75.1.2.2, and her.0.9.1.2.1; Figs. 6b, 6c, 7b, 7c, 8b, 8c, and 9b) there is some consistency of effect. In the cod like stocks and the high productivity herring like stock with no linear increase in the catchability (i.e. cod.0.75.1.2.1, cod.0.9.1.2.1, and her.0.9.1.2.1) this HCR led to a rapid large decline in fishing mortality as the stock moved away from the condition at F_{MSY} to $F_{0.1}$ (rather than F_{sq}). In each of these cases the yield also drops immediately as does the revenue. The profits in the cod like species stay stable and then climb whereas for the herring like species the profits too decline initially and then recover to higher levels than the starting values. In all cases there is a significant increase in the SSB and, especially in the cod like species a significant increase in the profits after about 10 years. There was no suggestion that fishery collapses could happen.

With the low productivity herring like stock (her.0.75.1.2.1) there was only a small decline in fishing mortality which in turn, led to small increases in SSB and profits but the yields and revenues appear to remain approximately the same through time.

There were examples of scenarios where the stocks were well managed but there was a linear increase in catchability that was unaccounted for in the assessment (cod.0.75.1.2.2, cod.0.9.1.2.2, and her.0.75.1.2.2). The responses were all similar to those for the respective scenarios that lacked the linear increase in catchability, however, the changes brought about by the management harvest control rule were muted. Thus, reductions in fishing mortality occurred but they were less rapid and of a smaller magnitude. Consequently, the effects on SSB were slowed as were those on profits, although the initial decline in yields was also less. One difference was fishery collapses became a possibility, though not common.

Because of time constraints within the workshop no examples of overfishing were examined using this second Harvest Control Rule.

With this Harvest Control Rule there were only example scenarios for the cod like stocks for those that were overfished (cod.0.75.3.2.1, cod.0.75.3.2.2, cod.0.9.3.2.1, and cod.0.9.3.2.2). Both the low and high productivity cod stocks (steepnesses 0.75 and 0.9; cod.0.75.3.2.1, and cod.0.9.3.2.1,) exhibited large and rapid declines in fishing mortality as soon as management began. Yields only decline very slightly until, after about 7 years yields increased and eventually recovered almost completely, although with a wide variation across the simulations. The drop in fishing mortality was associated with an immediate drop in costs and so profits immediately increased and carried on increasing through time. The SSB also began to recover, after about 7 years, and returned to undepleted levels by the end of 30 years. The two equivalent scenarios that included a linear increase in catchability (cod.0.75.3.2.2, and cod.0.9.3.2.2) exhibited very similar patterns to their counterparts except that once again the effects were rather muted so that there was a less dramatic decrease in fishing mortality and somewhat smaller increases in profits and SSB. The effect of the linear increase in catchability was to reduce the positive nature of improvements to the stocks.

In summary, fishing mortality tended to drop in all cases, which in many cases led to an equivalent drop in yields, however, because costs were significantly reduced most often profits were initially unaffected. The SSB tended to increase and over a period yields recovered and increased as did revenue, with profits often increasing. Imposing a bias by adding a linear increase in catchability through time always had the effect of muting or reducing any positive impacts of the HCR, at the same time, fishery collapses became a risk.

8.5. Model Free HCR

There was only one scenario which demonstrated the use of the model free harvest control rule (cod.0.9.1.4.1; Fig 6d) and this was a well managed relatively productive cod like stock (steepness = 0.9). The effect of this HCR was to bring about an immediate and rapid increase in fishing mortality which led initially to a small increase in yields. However, this was followed quickly by catastrophic decreases in SSB, yields, profits and recruits. Almost all simulation runs ended in fishery collapse. This particular model free strategy was clearly unworkable and alternatives were required.

Table 5. Alternative Operating Model scenarios. Selectivity change implies the same as management procedure 1 (Fy+2 = Max(F0.1,Fsq) plus a selectivity change on immature fish.

Scenario	Steepness	Status	MP	OEM
cod.0.9.1.1.1	0.9	Well Managed	Fy+2 = Max(F0.1,Fsq)	30% CV on CE
cod.0.9.1.2.1	0.9	Well Managed	Fy+2 = F0.1	30% CV on CE
cod.0.9.1.2.2	0.9	Well Managed	Fy+2 = F0.1	30% CV on CE + trend in q
cod.0.9.1.4.1	0.9	Well Managed	Model Free	30% CV on CE
cod.0.9.3.1.1	0.9	Overfished	Fy+2 = Max(F0.1,Fsq)	30% CV on CE
cod.0.9.3.2.1	0.9	Overfished	Fy+2 = F0.1	30% CV on CE
cod.0.9.3.2.2	0.9	Overfished	Fy+2 = F0.1	30% CV on CE + trend in q
cod.0.9.1.3.1	0.9	Well Managed	Selectivity Change	30% CV on CE
cod.0.9.2.3.1	0.9	Overfishing	Selectivity Change	30% CV on CE
cod.0.9.3.3.1	0.9	Overfished	Selectivity Change	30% CV on CE
cod.0.75.1.1.1	0.75	Well Managed	Fy+2 = Max(F0.1,Fsq)	30% CV on CE
cod.0.75.1.2.1	0.75	Well Managed	Fy+2 = F0.1	30% CV on CE
cod.0.75.1.2.2	0.75	Well Managed	Fy+2 = F0.1	30% CV on CE + trend in q
cod.0.75.2.1.1	0.75	Overfishing	Fy+2 = Max(F0.1,Fsq)	30% CV on CE
cod.0.75.3.1.1	0.75	Overfished	Fy+2 = Max(F0.1,Fsq)	30% CV on CE
cod.0.75.3.2.1	0.75	Overfished	Fy+2 = F0.1	30% CV on CE
cod.0.75.3.2.2	0.75	Overfished	Fy+2 = F0.1	30% CV on CE + trend in q
cod.0.75.1.3.1	0.75	Well Managed	Selectivity Change	30% CV on CE
cod.0.75.2.3.1	0.75	Overfishing	Selectivity Change	30% CV on CE
cod.0.75.3.3.1	0.75	Overfished	Selectivity Change	30% CV on CE
her.0.75.1.1.1	0.75	Well Managed	Fy+2 = Max(F0.1,Fsq)	30% CV on CE
her.0.75.1.2.1	0.75	Well Managed	Fy+2 = F0.1	30% CV on CE
her.0.75.1.2.2	0.75	Well Managed	Fy+2 = F0.1	30% CV on CE + trend in q
her.0.75.2.1.1	0.75	Overfishing	Fy+2 = Max(F0.1,Fsq)	30% CV on CE
her.0.75.3.1.1	0.75	Overfished	Fy+2 = Max(F0.1,Fsq)	30% CV on CE
her.0.75.1.3.1	0.75	Well Managed	Selectivity Change	30% CV on CE
her.0.75.2.3.1	0.75	Overfishing	Selectivity Change	30% CV on CE
her.0.75.3.3.1	0.75	Overfished	Selectivity Change	30% CV on CE
her.0.9.1.1.1	0.9	Well Managed	Fy+2 = Max(F0.1,Fsq)	30% CV on CE
her.0.9.1.2.1	0.9	Well Managed	Fy+2 = F0.1	30% CV on CE
her.0.9.2.1.1	0.9	Overfishing	Fy+2 = Max(F0.1,Fsq)	30% CV on CE
her.0.9.1.3.1	0.9	Well Managed	Selectivity Change	30% CV on CE
her.0.9.2.3.1	0.9	Overfishing	Selectivity Change	30% CV on CE
her.0.9.3.3.1	0.9	Overfished	Selectivity Change	30% CV on CE

Table 6. Scenario summaries.

Scenario	F	SSB	Collapse	Profits	Yields
cod.0.9.1.1.1	Slow increase	Slow reduction	Possible	Slightly down	Increased variation
cod.0.9.1.2.1	Rapid decrease	Up after 5 years	No	Up after 7 yrs	decline followed by increase
cod.0.9.1.2.2	Some decrease	Up after 7 years	Possible	Up after 10 yrs	Small decline small increase
cod.0.9.1.4.1	Rapid rise	Mostly collapse	Common	Rapidly negative	Initial increase then collapse
cod.0.9.1.3.1	Slow increase	Slowly down more variable	No	More variable	Stable
cod.0.9.2.3.1	Slow decline, more variable	More variable, up at end	Possible	Slowly up, more variable	More variable, up at end.
cod.0.9.3.1.1	Slight slow decline	Up after 5 years	Possible	Up after 5 yrs	Up after 5years, 2/3 recovered
cod.0.9.3.2.1	Rapid decrease	Up after 5 years	No	Up after 3 yrs	Up after 7 years, recovers
cod.0.9.3.2.2	Some decrease	Up after 7 years	No	Up after 3 yrs	Up after 7 years, recovers
cod.0.9.3.3.1	Slow decline, more variable	Stable, up after 5 yrs	Possible	Up on 5yrs to recovery	Up on 5 yrs to recovery.
cod.0.75.1.1.1					
cod.0.75.1.2.1	Rapid decrease	Recovers 25 yrs	No	Up after 7 yrs	decline followed by increase
cod.0.75.1.2.2	Some decline	Slow recovery	Possible	Up after 10 yrs	small decline, increase after 10yrs
cod.0.75.1.3.1	More variable, down at end	More variable, down at end	Possible	More variable, down at end	More variable, down at end.
cod.0.75.2.1.1	Large increase variation	More variable	Possible	rarely positive	Increased variation, no improvement
cod.0.75.2.3.1	Slightly down, more variable	More variable	Possible	Rarely positive, variable	More variable, up at end.
cod.0.75.3.1.1	Small decrease, variation up	Up after 7 yrs	Possible	Up but variable	Up but variable.
cod.0.75.3.2.1	Rapid decrease	Recovers 25 yrs	No	Up after 3 yrs	Up after 7 yrs
cod.0.75.3.2.2	Some decline	Up after 5 yrs	Possible	Up slowly	Up after 5 yrs, more variable.
cod.0.75.3.3.1	Slightly up, more variable	Recovers after 30 years	Possible	Recovers after 30yrs	Recovers after 30 yrs.
her.0.75.1.1.1	Increase variation	variation up slightly	No	More variable	No effect
her.0.75.1.2.1	Slight decrease	Slight increase	No	Slight increase	minor increase
her.0.75.1.2.2	Small decrease	Small increase	No	Small increase	More variable
her.0.75.1.3.1	Slightly more variable	Stable	No	Stable	Stable

Table 6 [cont.]

Scenario	F	SSB	Collapse	Profits	Yields
her.0.75.2.1.1	Slow decrease	Slow increase	No	Slow increase	No change
her.0.75.2.2.1					
her.0.75.2.3.1	Slow decrease	Slow increase after 7 yrs	No	Stable then up after 7 yrs	Minor down for 10 yrs then slightly up
her.0.75.3.1.1	Initially down then steady	Stable, then up and variable	Possible	Slowly up but variable	Stable, then up and increased variation.
her.0.75.3.3.1	Initially up then rapid down	Stable, then recover 20 yrs	No	Stable, recover 20 yrs	Stable then recovers in 20 yrs
her.0.9.1.1.1	Slow small decline	Slow small increase	No	No change	Very slightly down
her.0.9.1.2.1	Large rapid decline	Up after 5yrs	No	Slightly down then Up	Initially down, then up but less than start
her.0.9.2.1.1	Rapid decline	Some recovery after 5yrs	No	Up after 8 yrs	Initially down, then back to starting level.
her.0.9.1.3.1	Initially up then slow decline	Very slow increase	No	Slightly up	Stable
her.0.9.2.3.1	Rapid decline	Some recovery after 5 yrs	No	Up after 8 yrs	Initially down, then back to starting level.
her.0.9.3.3.1	Rapid decline	Recovery by 10 yrs	No	Recover after 12 yrs	Stable till 5yrs then up to recovery.

Cod Stock with Steepness of 0.9

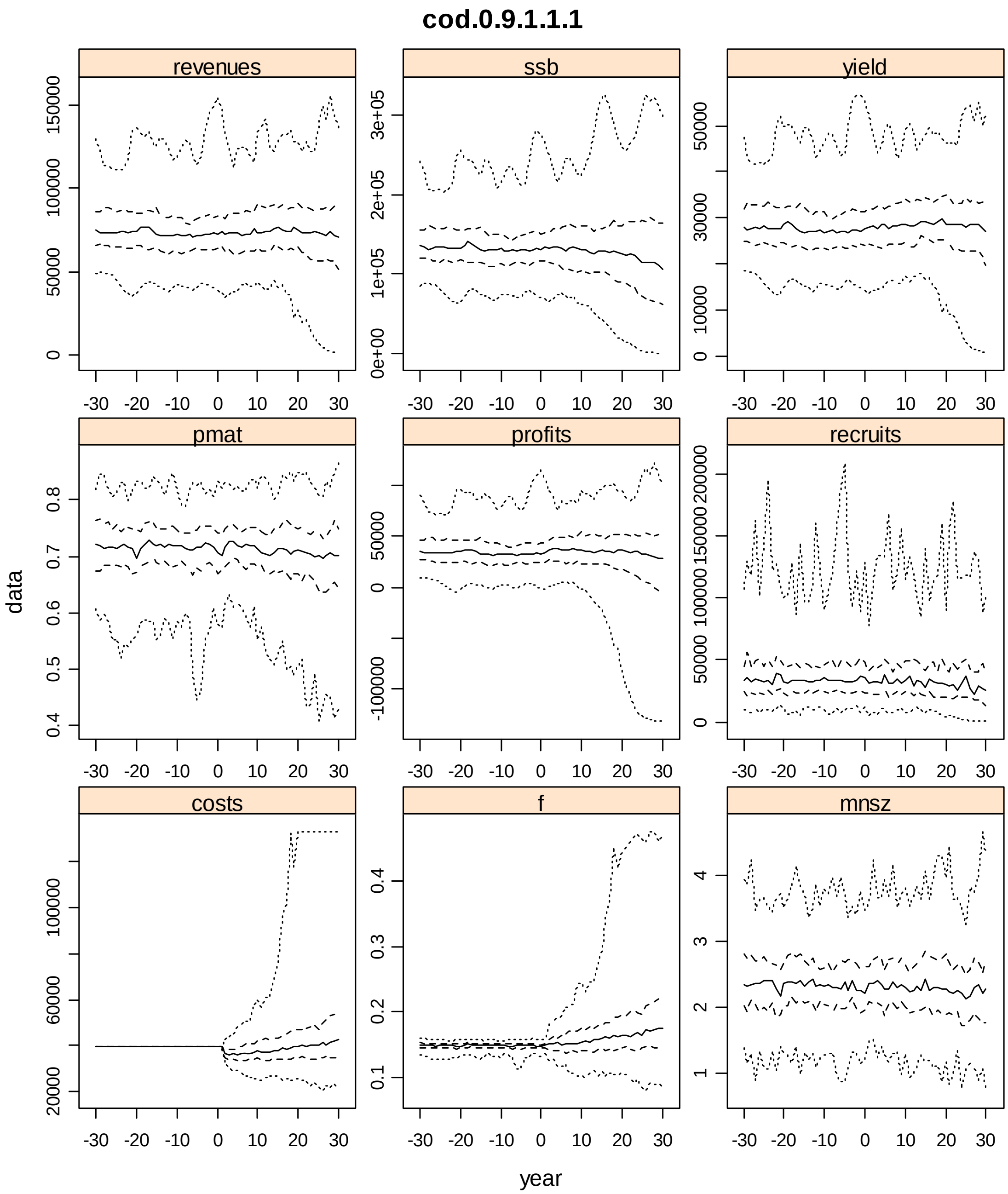

Figure 6a. A well managed cod stock with a steepness of 0.9 using the VPA HCR and an observation error of 30% CV on the CPUE data. The HCR leads to a slow increase in fishing mortality leading to a gradual decline in SSB with increases in the variation in yield, a small reduction in profits and a slight reduction in recruitment.

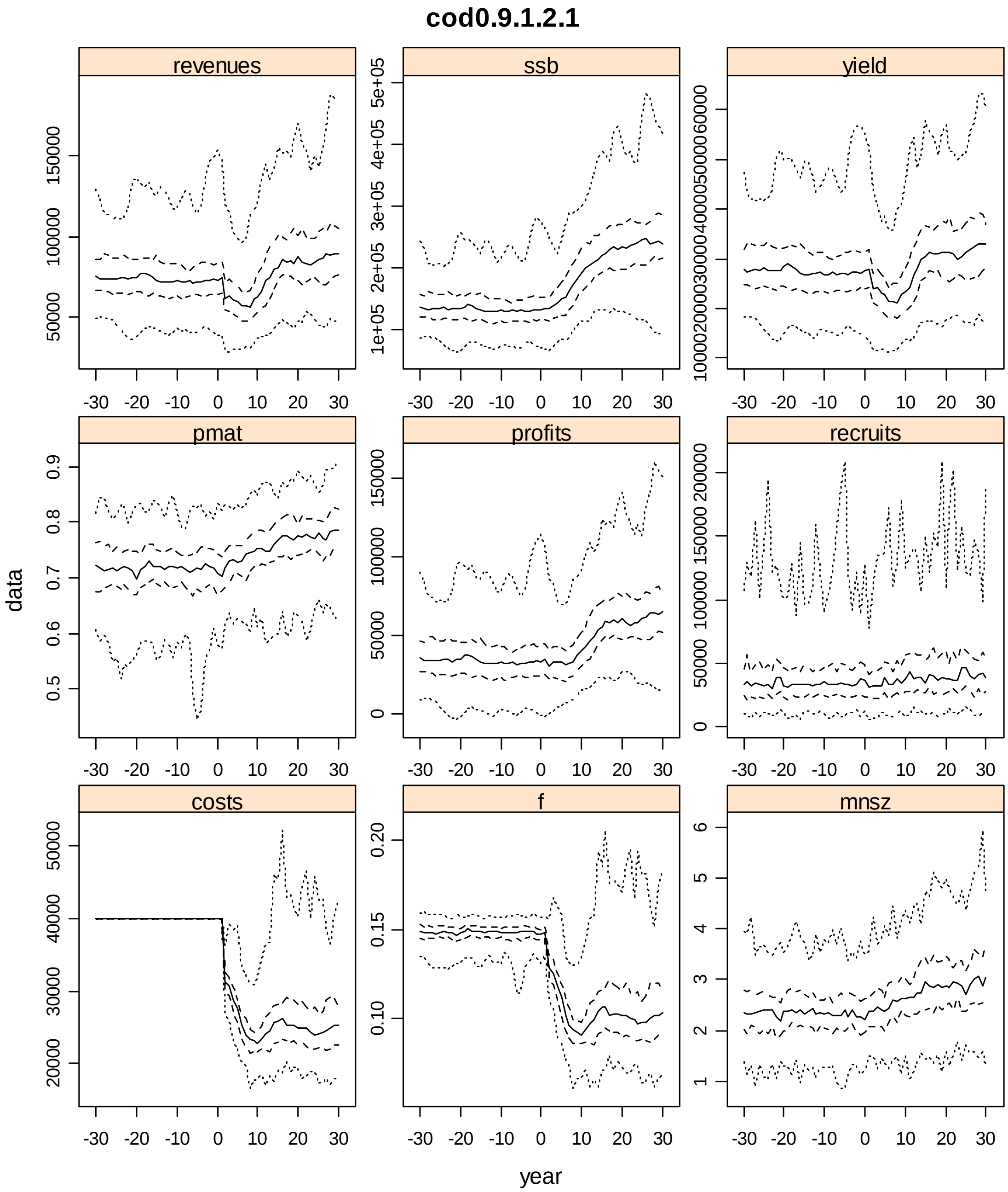

Figure 6b. A well managed cod stock with a steepness of 0.9 using the VPA HCR but focused on $F_{0.1}$ rather than choosing between $F_{0.1}$ and F_{sq}, and an observation error of 30% CV on the CPUE data. The HCR leads to an immediate and rapid drop in fishing mortality which rapidly drops costs (but also initially revenues) and yields. After about 10 years the increases in spawning stock size lead to an increase in profits, revenues, and yields until after about 15 years the yields, profits and revenue are all higher than initially, with the spawning stock size being almost twice the initial size and the mean size of fish has also increased.

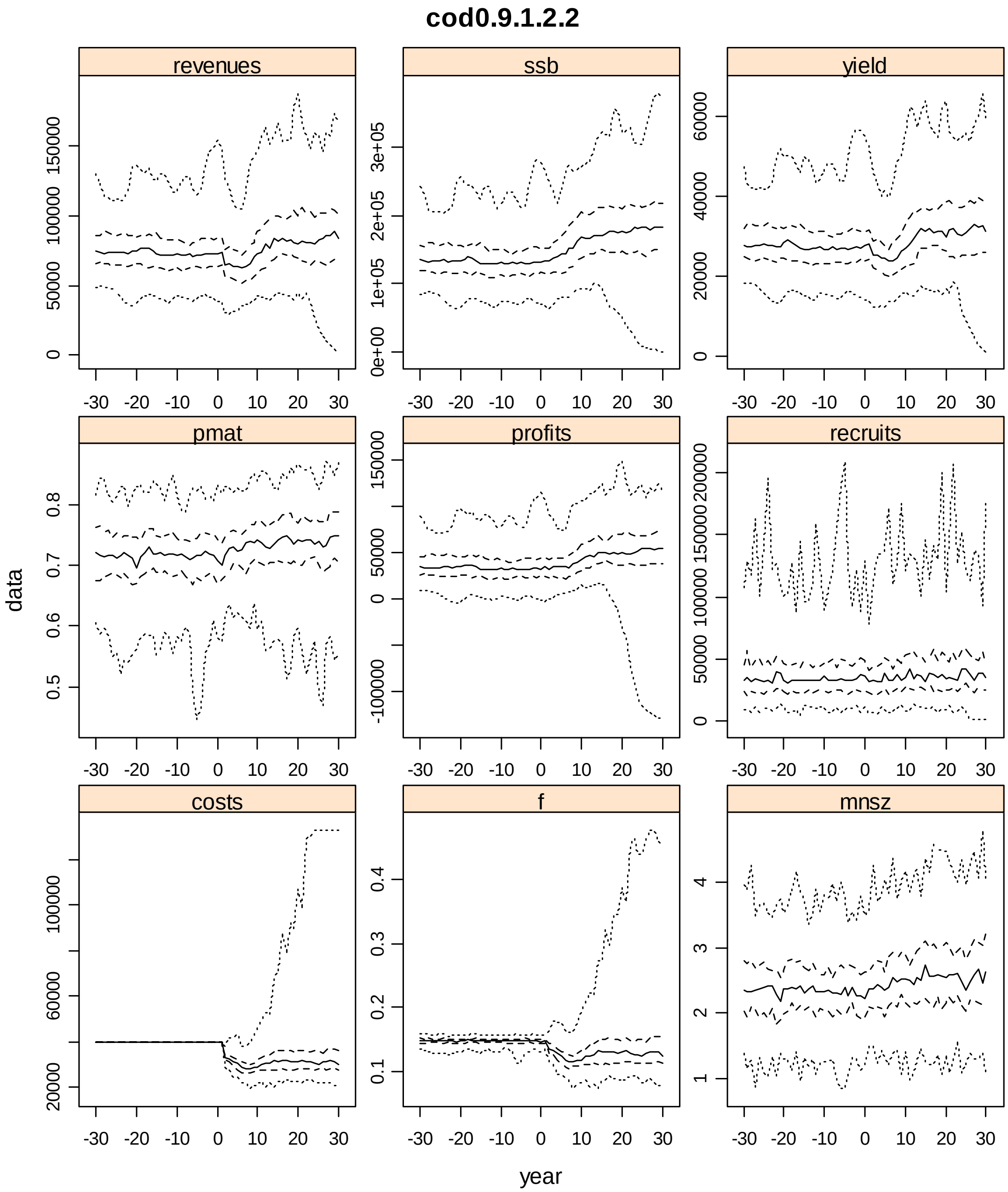

Figure 6c. A well managed cod stock with a steepness of 0.9 using the VPA HCR but focused on $F_{0.1}$ rather than choosing between $F_{0.1}$ and F_{sq}, and an observation error of 30% CV on the CPUE data plus a linear increase in catchability through time. This had the effect of slightly reducing the rate and size of the decrease in fishing mortality that occurred in the first 5 years with a few of the runs experiencing relatively high fishing mortalities which in turn increased costs and lost profits and led to stock depletion. However, the median changes to the fishery were similar to those in cod.0.9.1.2.1 except that the changes were less marked and achieved a plateau where in cod.0.9.1.2.1 improvements in spawning stock biomass, yield, revenue and profits continued to increase through time, if only slowly. The effect of the linear increase in catchability was to temper the changes in the stock but not remove the improvement completely.

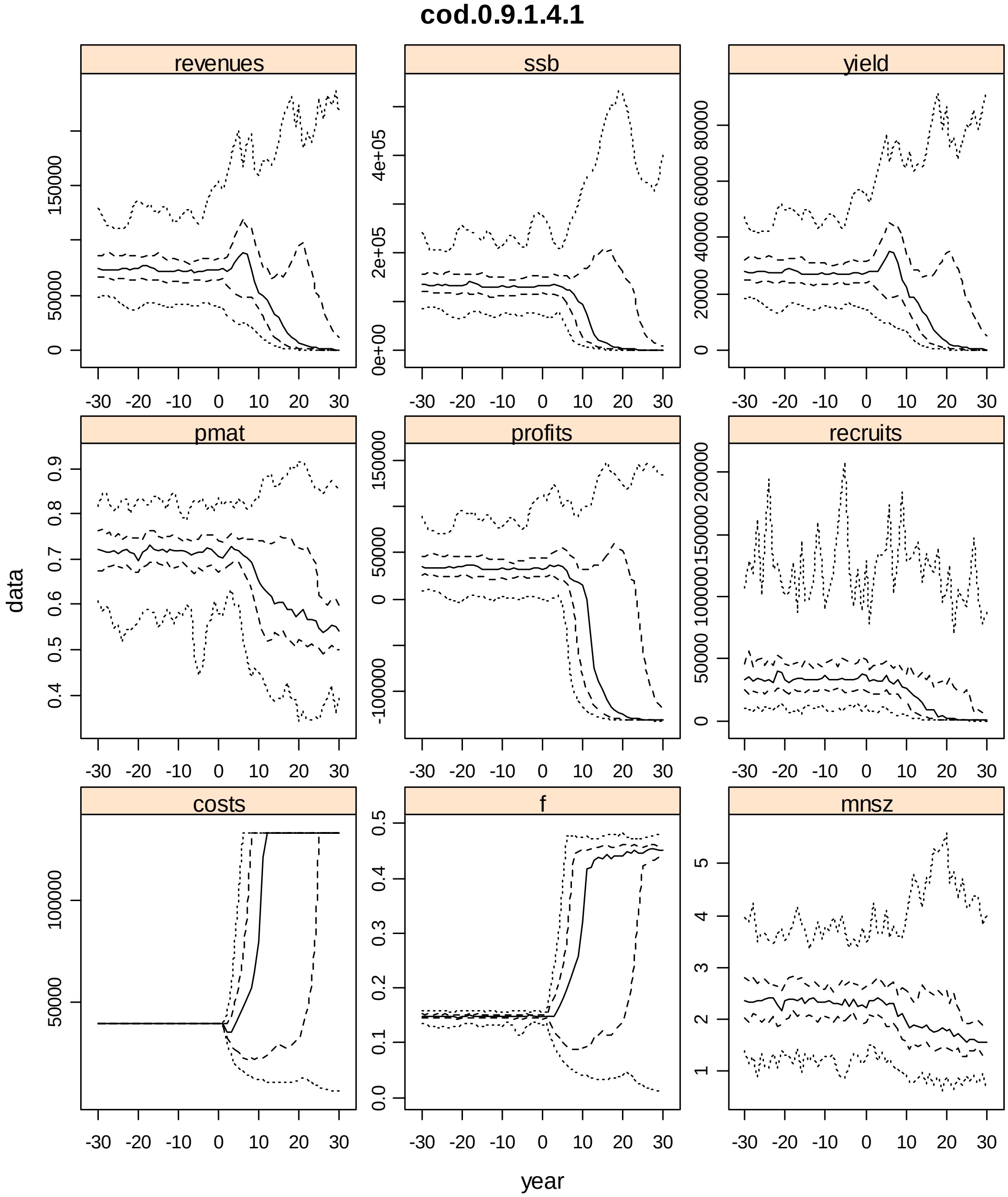

Figure 6d. A well managed cod stock with a steepness of 0.9 using a model free HCR, and an observation error of 30% CV on the CPUE data. This HCR failed to achieve successful management leading to runaway increases in fishing mortality leading in turn to increased costs, a depletion of spawning stock biomass, drops in yield, profits, revenues, mean size, and recruitment. further work on the model free HCR is required.

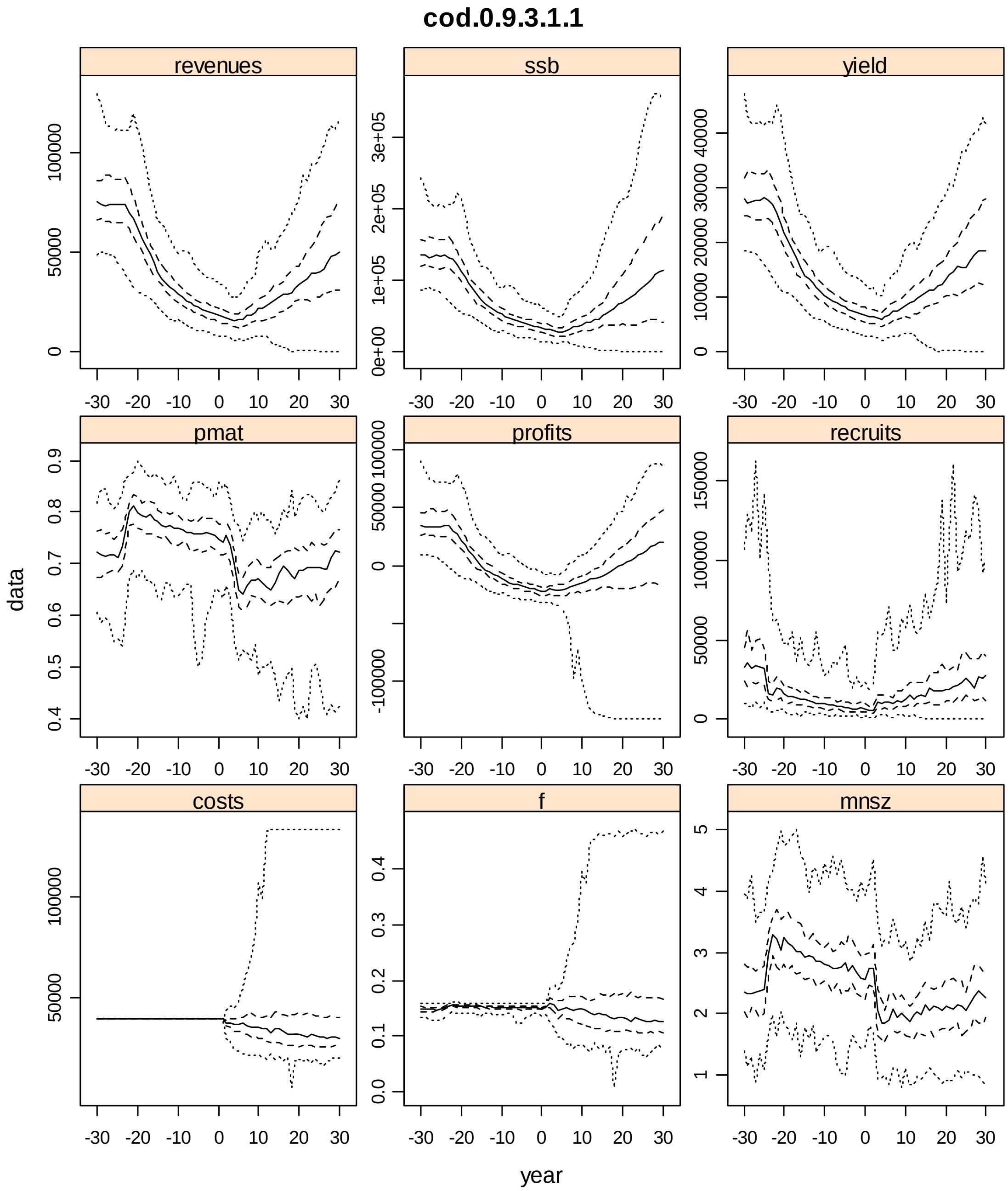

Figure 6e. An overfished cod stock with a stock recruitment steepness of 0.9 and a VPA based HCR that takes the maximum of $F_{0.1}$ and F_{sq}, combined with an observation error model that imposes a 30% CV on CE data. This HCR leads to a slow and gradual decline in fishing mortality which, after a continued minor decline in the stock for the first four or five years, leads to a reduction in costs and a slow increase in spawning stock biomass, in yield, and in revenue. After thirty years the stock has still not recovered completely and in some of the runs there is an indication of a fishery collapse with stock size, yield, revenue and other indicators going at least close to zero.

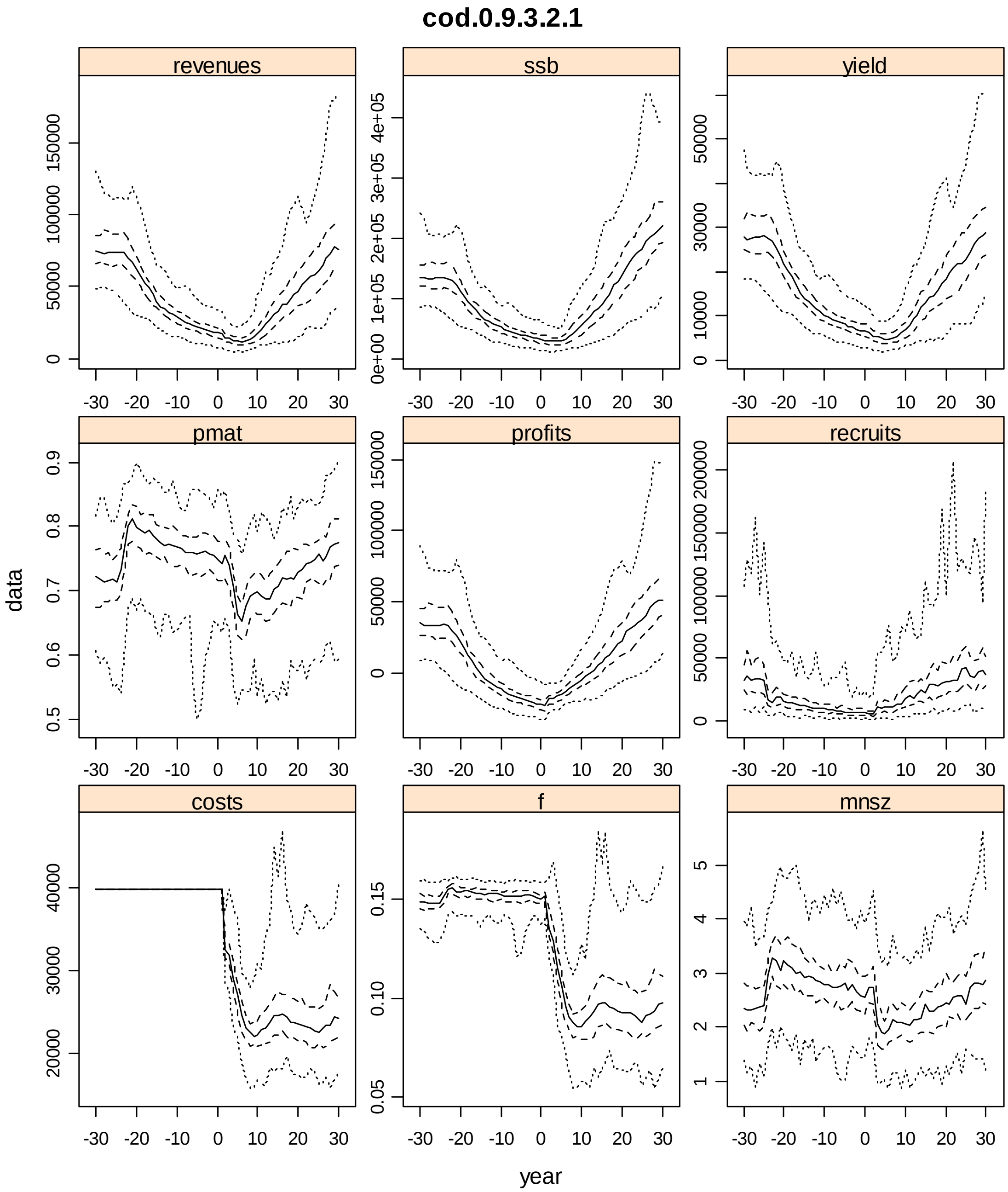

Figure 6f. An overfished cod stock with a stock recruitment steepness of 0.9 and a VPA based HCR that focuses on $F_{0.1}$, combined with an observation error model that imposes a 30% CV on CE data. This is obviously similar to cod.0.9.3.1.1 except for the slightly different HCR. The difference in behaviour, however, is marked. There is an immediate and rapid reduction in fishing mortality which leads to a rapid decrease in costs with a smaller reduction in revenues so that the profits quickly increase. The increase in spawning stock biomass appears to begin immediately management action begins and the stock recovers to optimum levels within 20 years, a marked improvement over the first HCR. There does not appear to be a risk of fishery collapse. The mean size initially decreases with the increase in recruitment but slowly increases back to initial sizes.

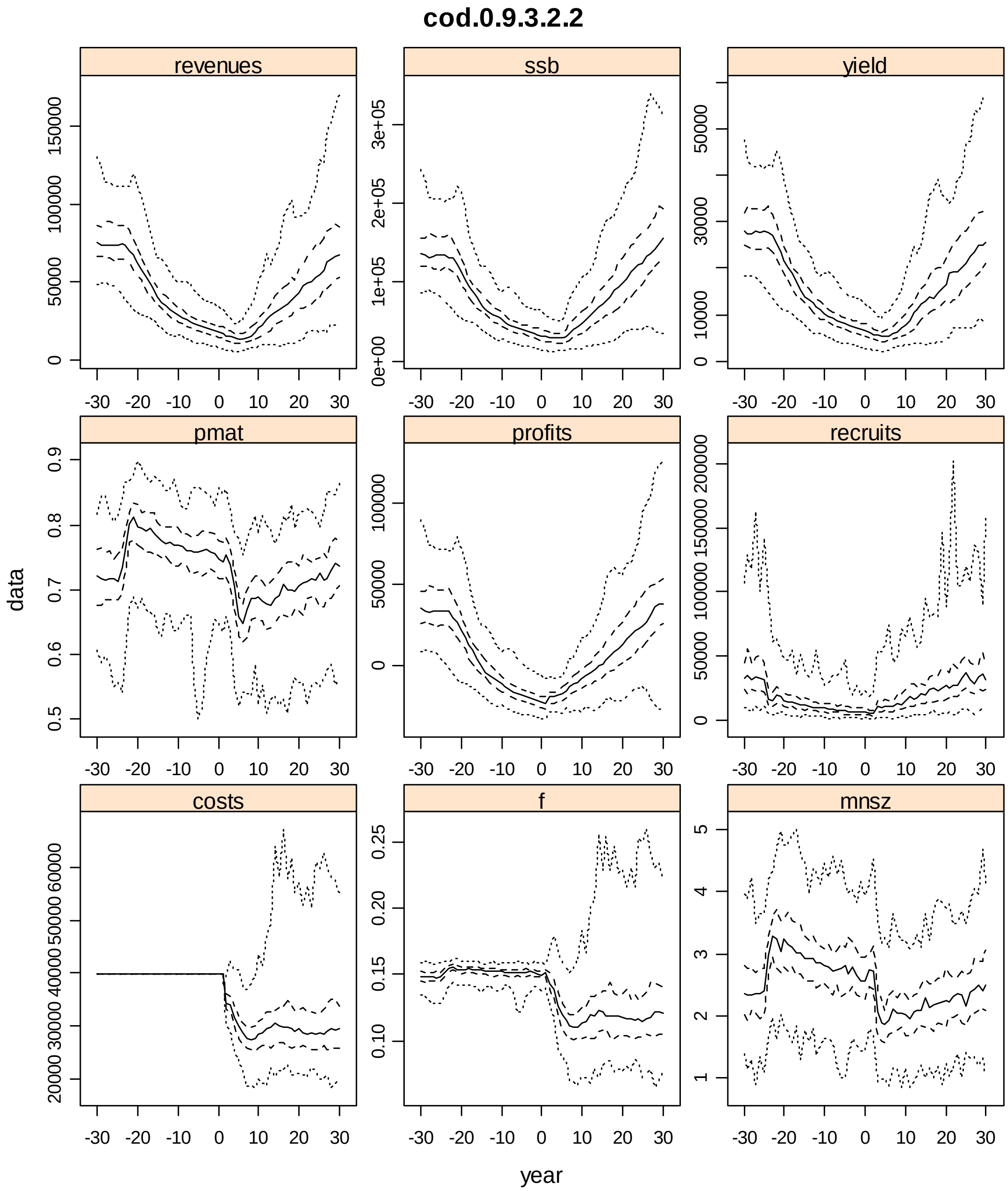

Figure 6g. An overfished cod stock with a stock recruitment steepness of 0.9 and a VPA based HCR that focuses on $F_{0.1}$, combined with an observation error model that imposes a 30% CV on CE data as well as a linear increase in catchability through time. This has similar behaviour to cod.0.9.3.2.1 except that the responses are more muted. Thus the reduction in fishing mortality is less and not so marked. Consequently the responses in terms of costs, revenue, profits, spawning stock biomass and recruits is also less marked. The stock recovers in size but takes 30 years to do so although yield increase at about the same rate. The mean size does not recover to the same extent and F remains slightly higher than with cod.0.9.3.2.1. Once again the effect of the linear increase in catchability is to slow the rate of recovery and to mute the effects of reducing fishing mortality.

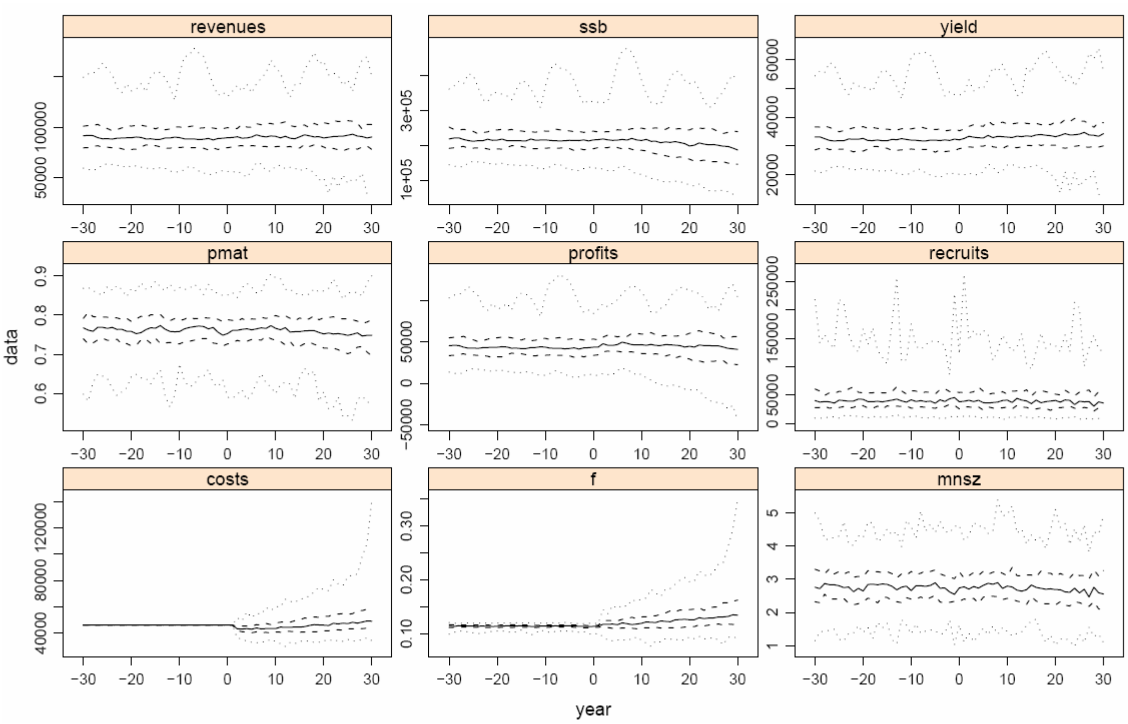

Figure 6h. cod.0.9.1.3.1, A well managed, highly productive (steepness = 0.9) cod stock, and a VPA based HCR with an addition of a change in selectivity for immature fish, and an observation error model that imposes a 30% CV on CE data.

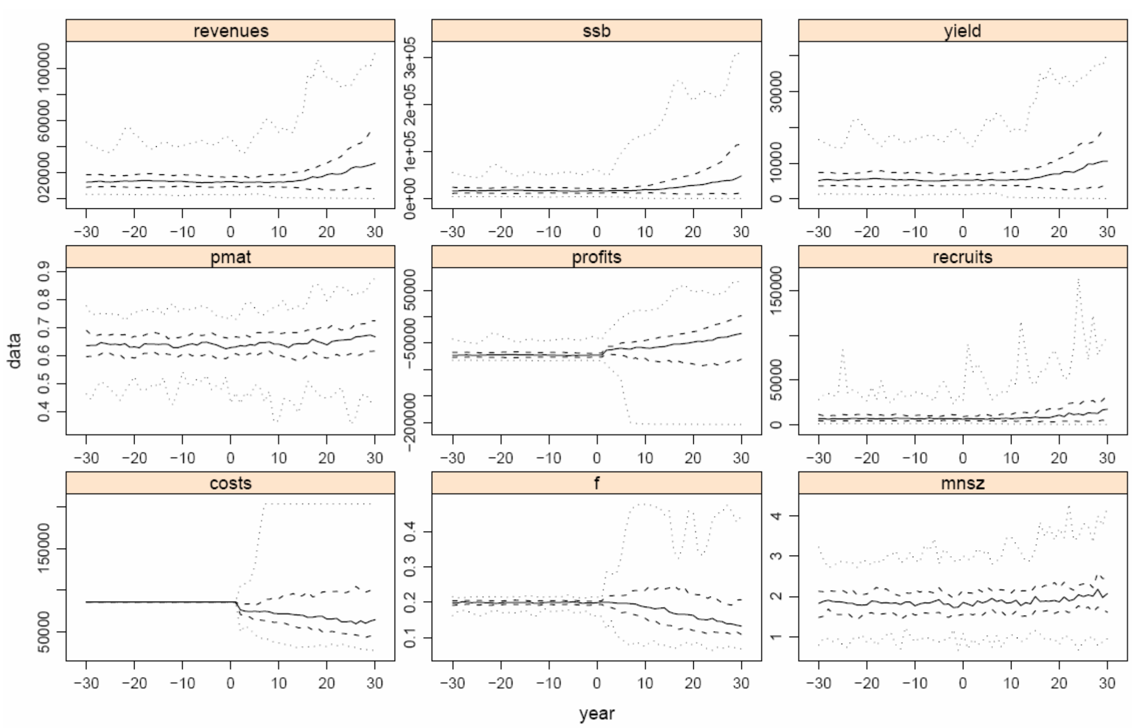

Figure 6i. cod.0.9.2.3.1. A highly productive (steepness = 0.9) cod stock experiencing overfishing, with a VPA based HCR with an addition of a change in selectivity for immature fish, and an observation error model that imposes a 30% CV on CE data.

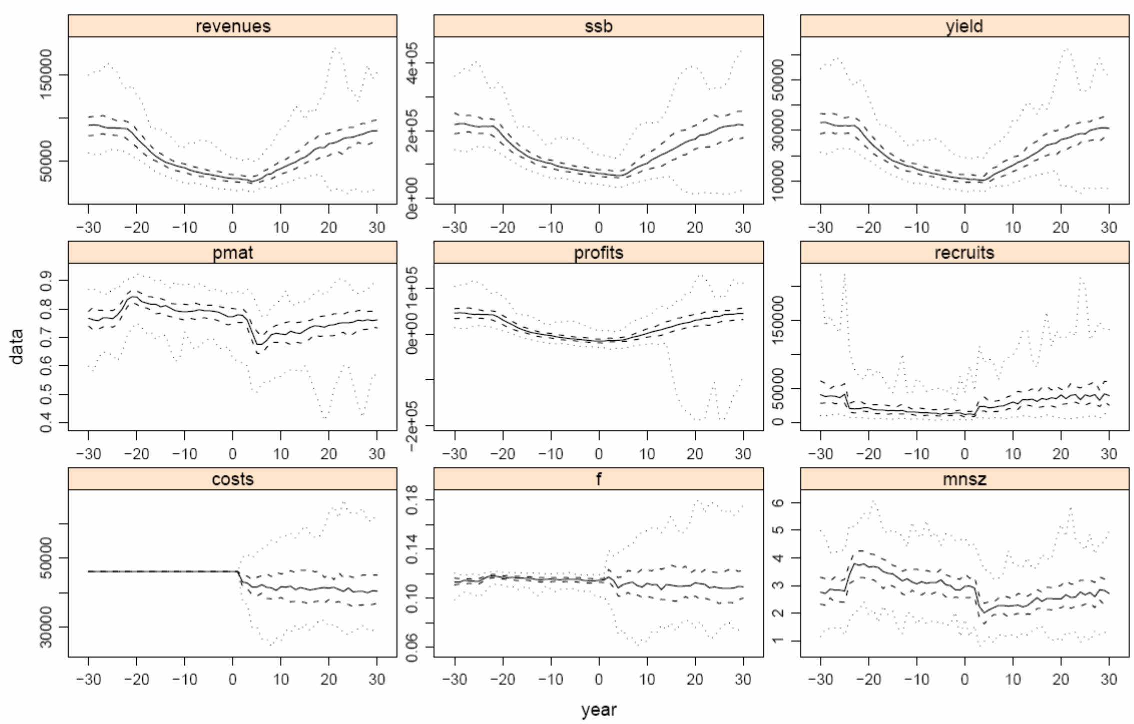

Figure 6j. cod.0.9.3.3.1. A highly productive (steepness = 0.9) overfished cod stock, with a VPA based HCR with an addition of a change in selectivity for immature fish, and an observation error model that imposes a 30% CV on CE data.

Cod stocks with a stock recruitment steepness of 0.75

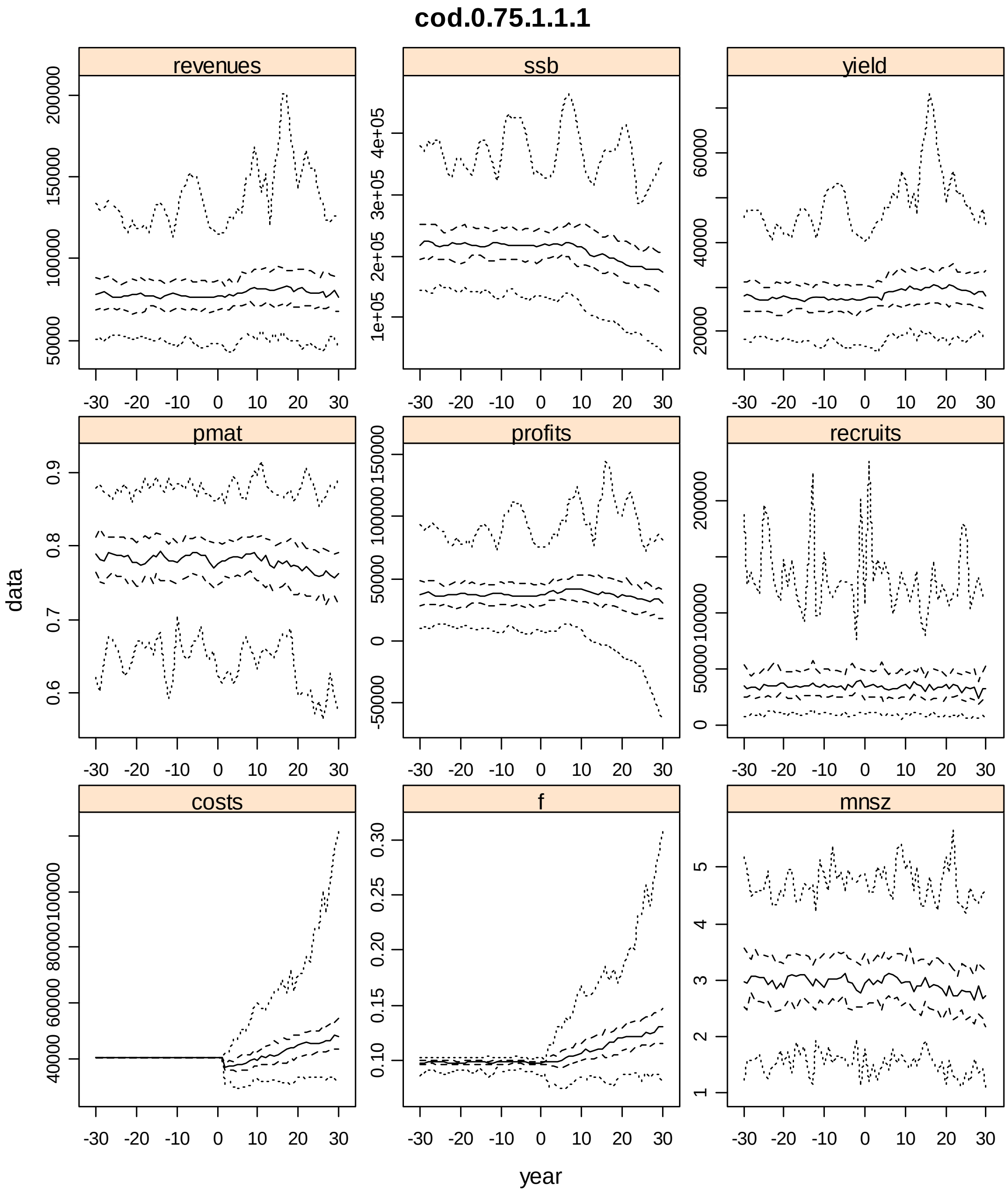

Figure 7a. A well managed cod stock with a steepness of 0.75 using the VPA HCR and an observation error of 30% CV on the CPUE data. After about five years fishing mortality begins to drift higher leading to slow stock declines increases in costs and a reduction in profits. Yield does not appear to alter although the mean size declines slightly as does the proportion mature. After 30 years the stock is in worse condition than when it starts

management.

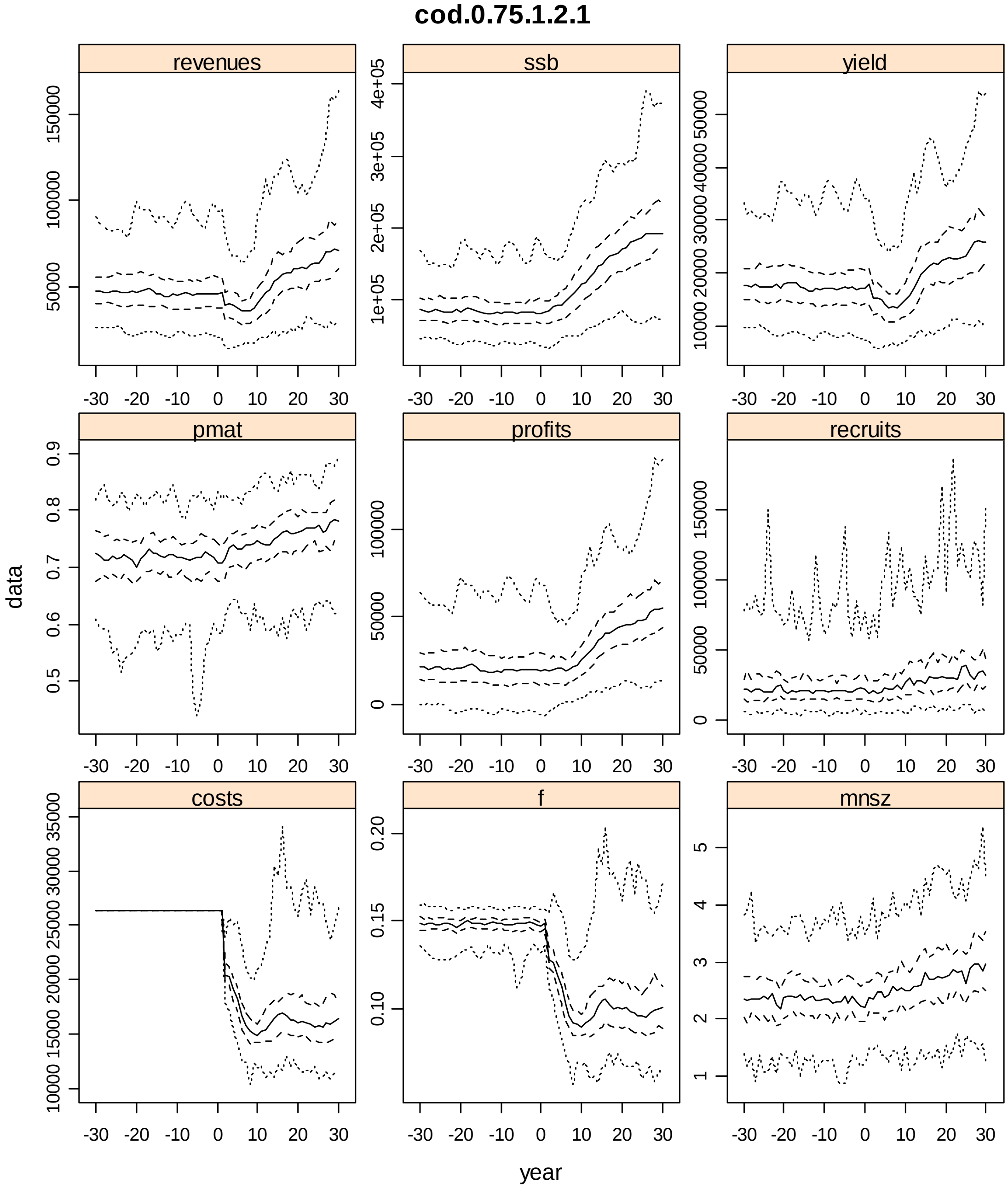

Figure 7b. A well managed cod stock with a steepness of 0.75 using the VPA HCR that focused on $F_{0.1}$and an observation error of 30% CV on the CPUE data. There is an immediate drop in fishing mortality (presumably from F_{MSY} to $F_{0.1}$, leading to an immediate drop in costs and revenues. But there is a rapid increase in spawning stock size so that after ten years revenues begin to increase again and soon build to higher levels than at the start of management. It takes 10 years, but after that time profits begin to rise along with spawning stock size, the yield, the revenues and the mean size.

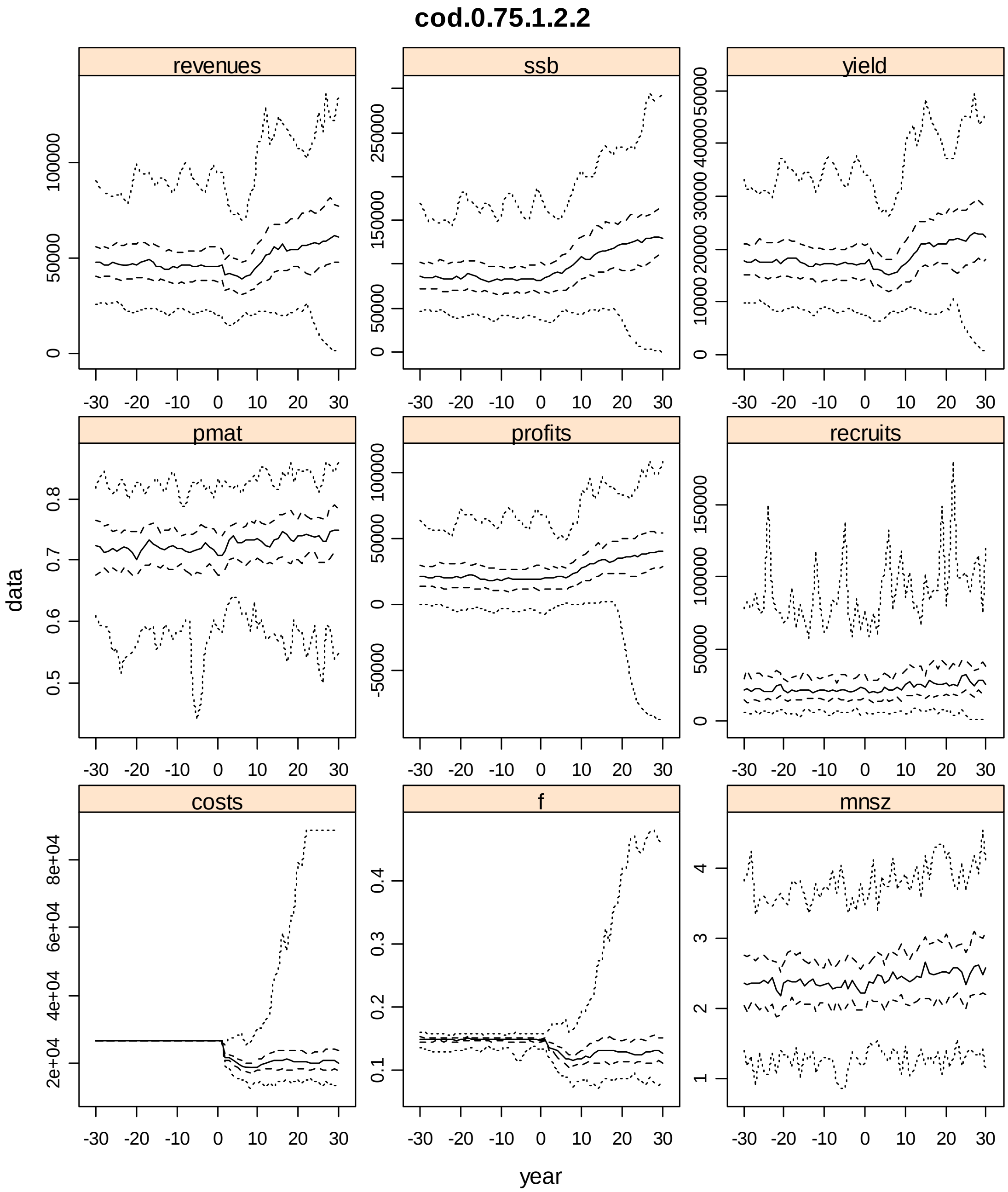

Figure 7c. A well managed cod stock with a steepness of 0.75 using the VPA HCR that focused on $F_{0.1}$ and an observation error of 30% CV on the CPUE data plus a linear increase in the catchability. Once again the effect of the linear increase in catchability is to mute the response to management. The drop in fishing mortality is not as marked and this influences both the extent and speed of changes in costs, revenues, profit and the spawning stock size. In a few instances the stock size drops to close to zero which is reflected by elevated costs, a lack of profits and weak revenue. The spawning stock size does increase on average but not to the same extent as without the linear increase in catchability.

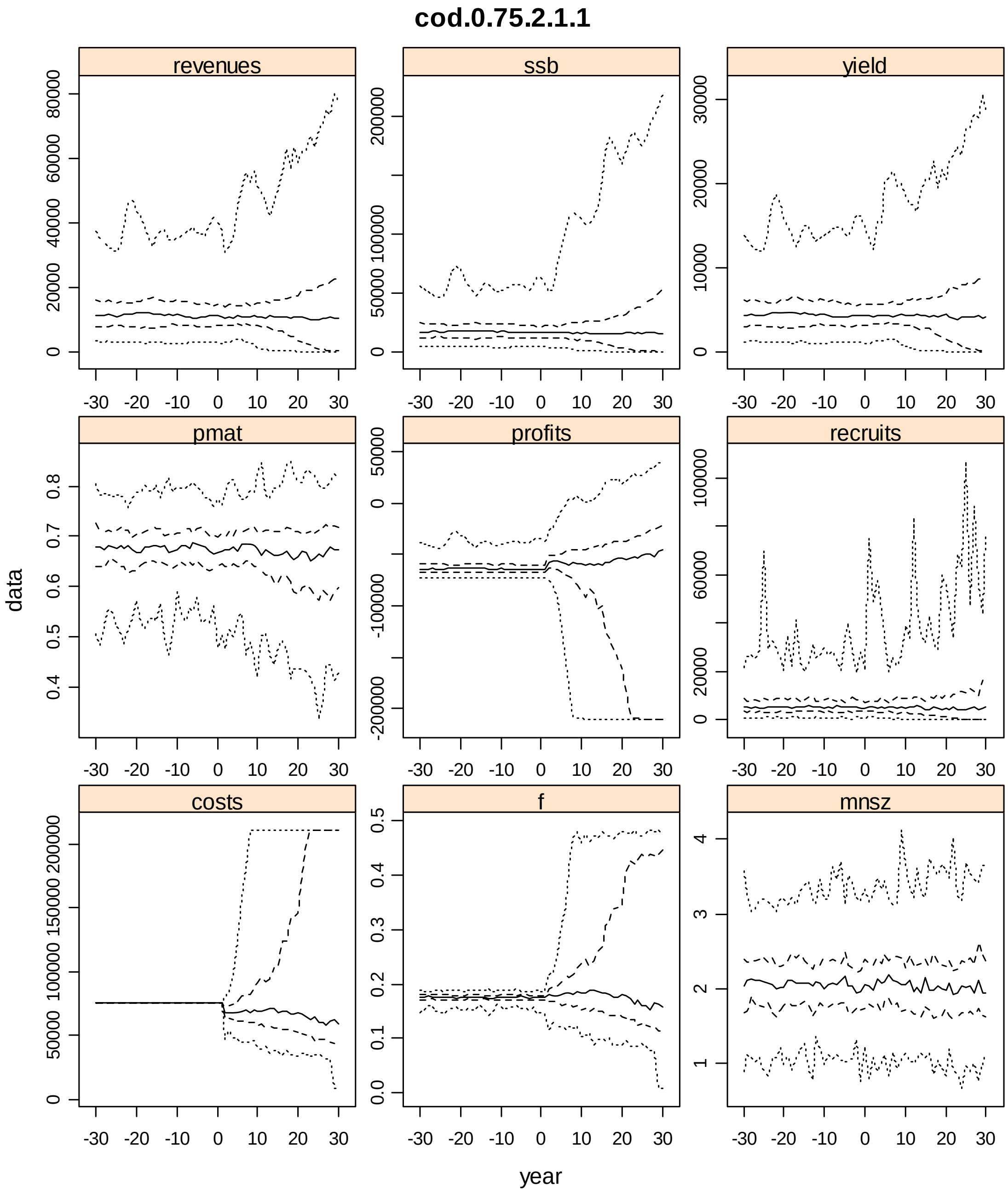

Figure 7d. A cod stock in which overfishing is occurring with a steepness of 0.75 using the VPA HCR that selects the maximum of $F_{0.1}$ and F_{sq}, and an observation error of 30% CV on the CPUE data. This HCR allows the overfishing to continue and leads to increasing variation in fishing mortality, increasing variation in spawning stock size but no median increase in SSB. In summary there is an increase in variation through the various statistics but not stock recovery no real change in yield and the fishery remains unprofitable through the 30 year management period.

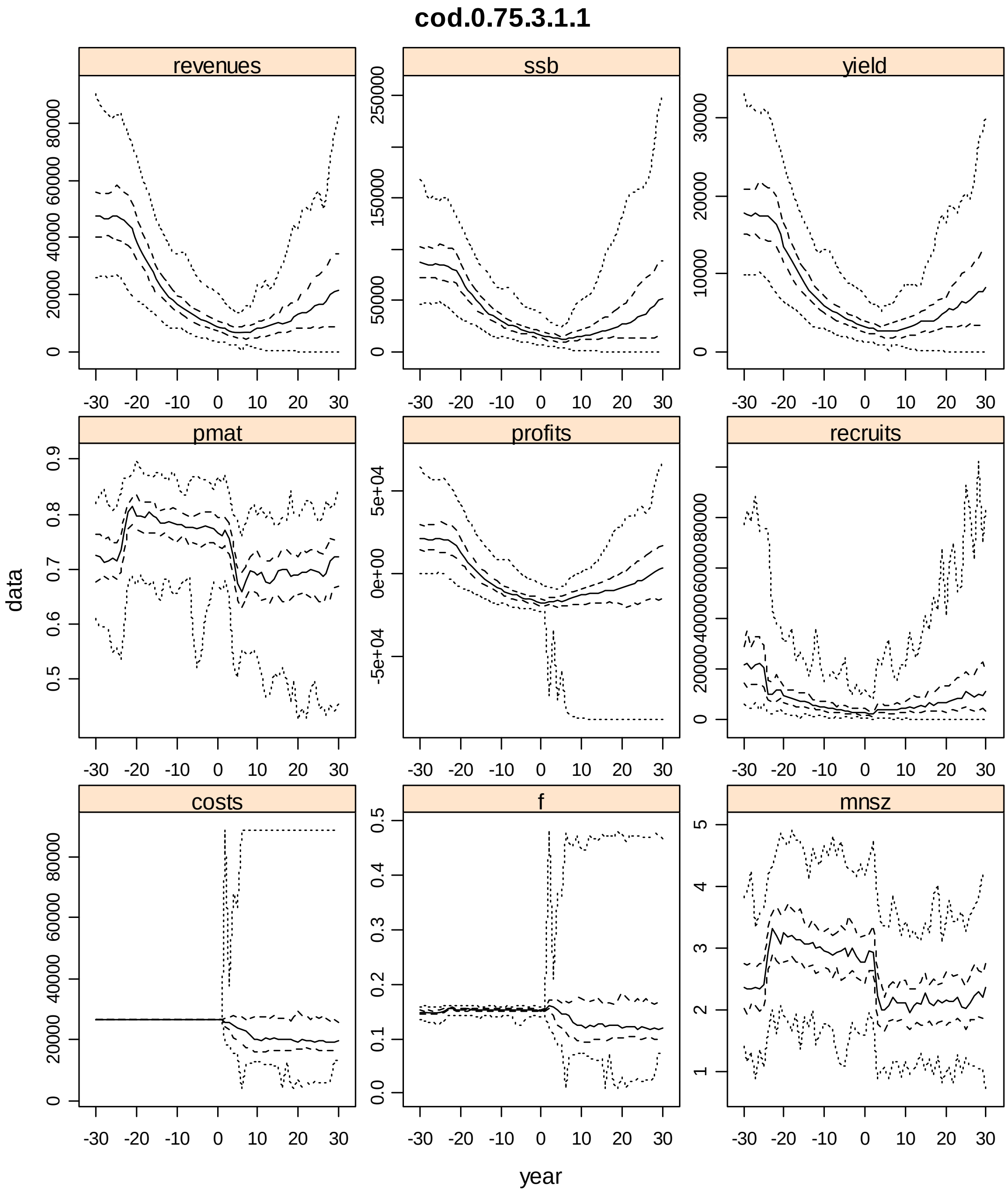

Figure 7e. A cod stock which is overfished with a steepness of 0.75 using the VPA HCR that selects the maximum of $F_{0.1}$ and F_{sq}, and an observation error of 30% CV on the CPUE data. Fishing mortality slowly declines leading to slow reductions in costs and a slow increase in SSB, although only after at least 10 years. This HCR does lead to some stock recovery over the 30 years of management but also increased variation with some runs leading to very low yields, profits, and revenues.

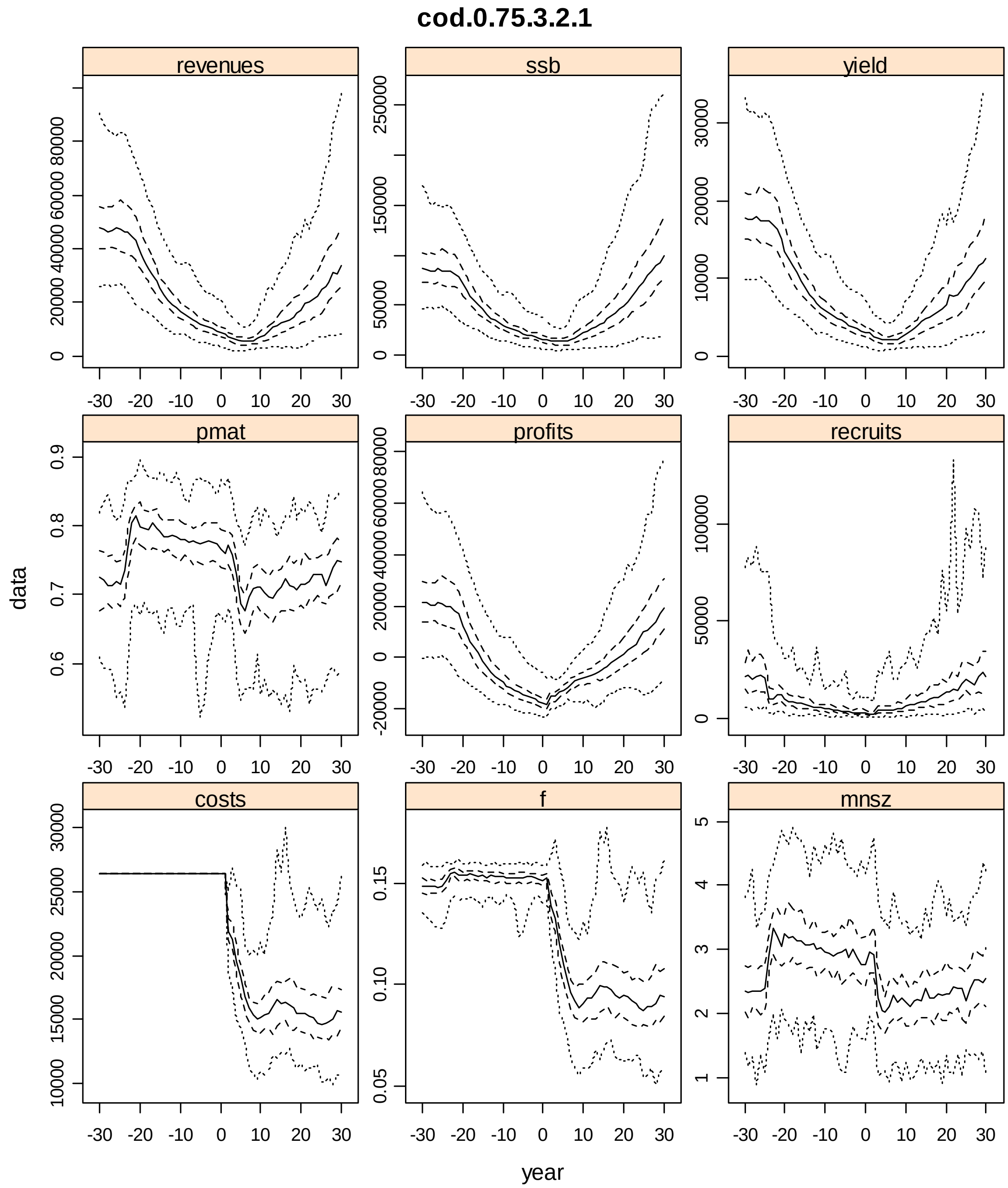

Figure 7f. A cod stock which is overfished with a steepness of 0.75 using the VPA HCR that selects the $F_{0.1}$, and an observation error of 30% CV on the CPUE data. This HCR immediate acts to reduce fishing mortality rapidly over the first ten years. This leads in turn to reductions in costs, but an increase in revenues and hence profits. After about 10 years the SSB begins to increase along with the yield and the number of recruits.

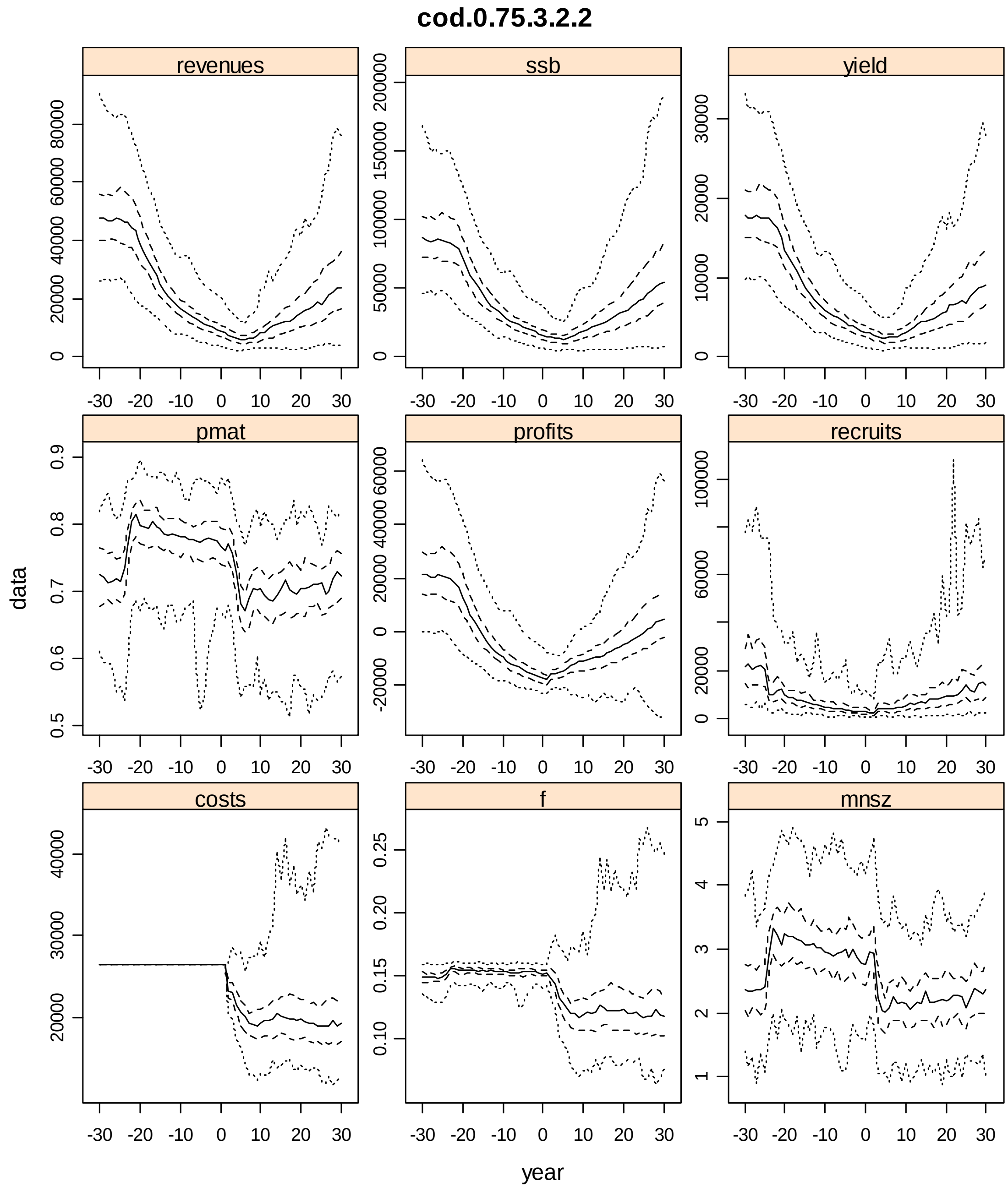

Figure 7g. A cod stock which is overfished with a steepness of 0.75 using the VPA HCR that selects the $F_{0.1}$, and an observation error of 30% CV on the CPUE data in addition to a linear in crease in catchability. Once again the linear increase in catchability has muted the responses to management. The reduction in fishing mortality is reduced with other changes following on in a less marked manner to that seen in cod.0.75.3.2.1. It still takes 10 years for the full effect of the reduction of fishing mortality to take effect, but the impacts are in all cases less marked. For example the SSB does not recover to the same extent as in cod.0.75.3.2.1.

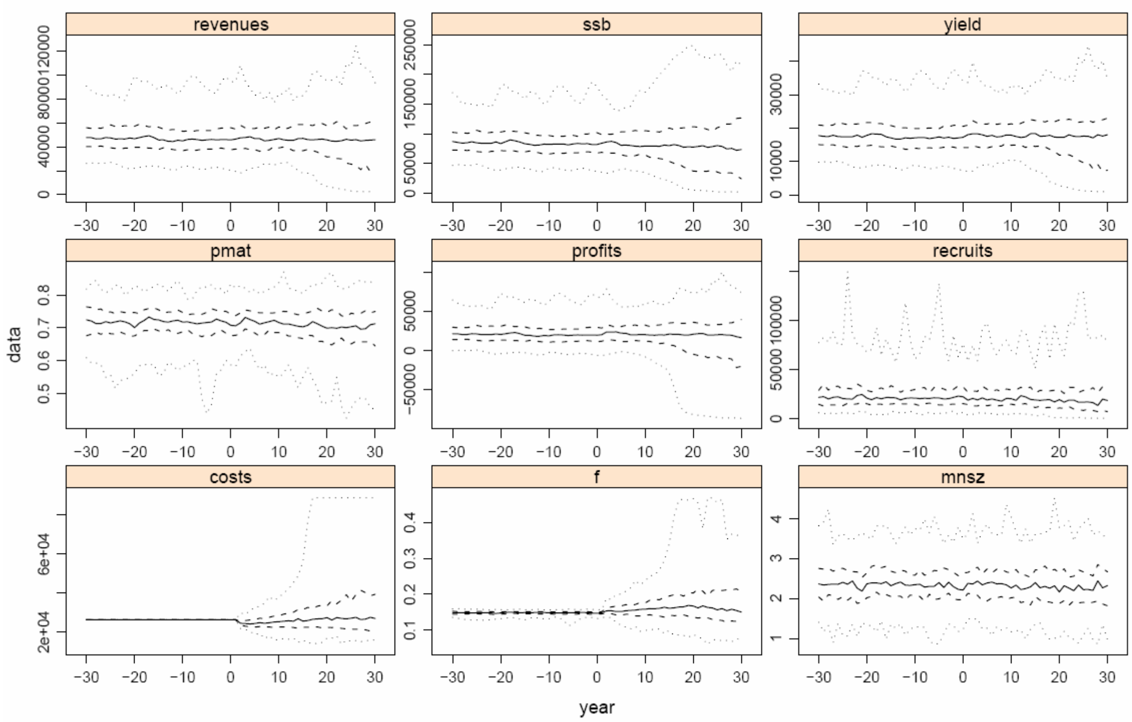

Figure 7h. cod.0.75.1.3.1. A well managed, low productivity (steepness = 0.75) cod like stock, with a VPA based HCR with an addition of a change in selectivity for immature fish, and an observation error model that imposes a 30% CV on CE data.

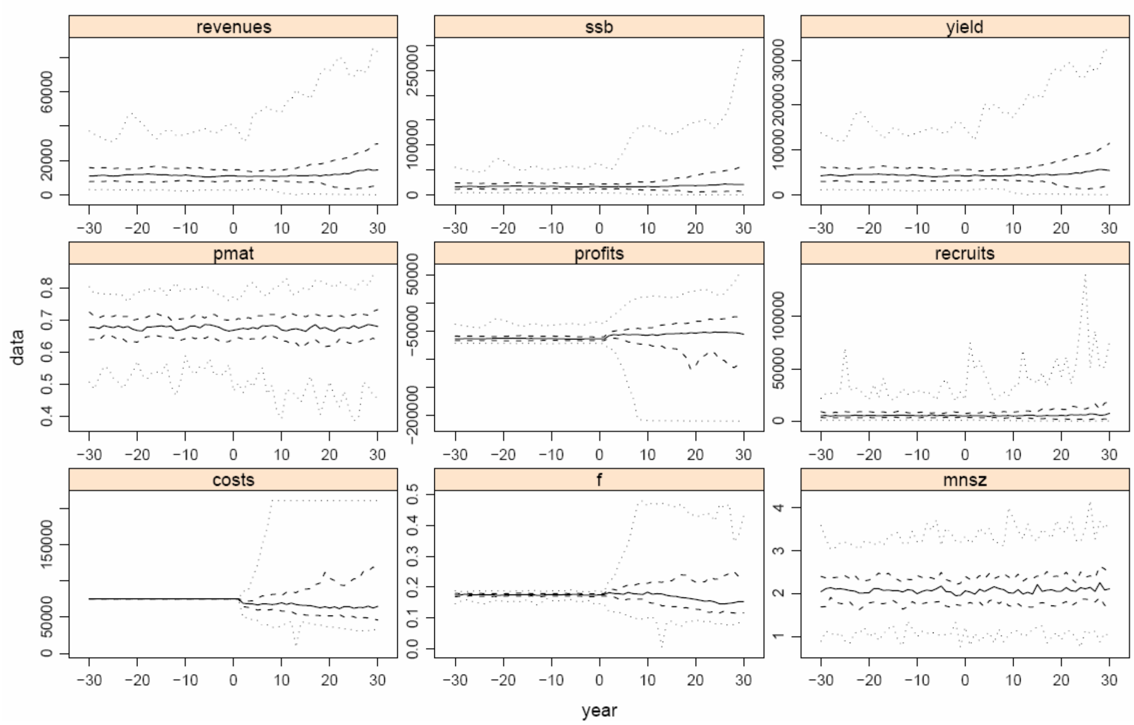

Figure 7i. cod.0.75.2.3.1. A low productivity (steepness = 0.75) cod like stock experiencing overfishing, with a VPA based HCR with an addition of a change in selectivity for immature fish, and an observation error model that imposes a 30% CV on CE data.

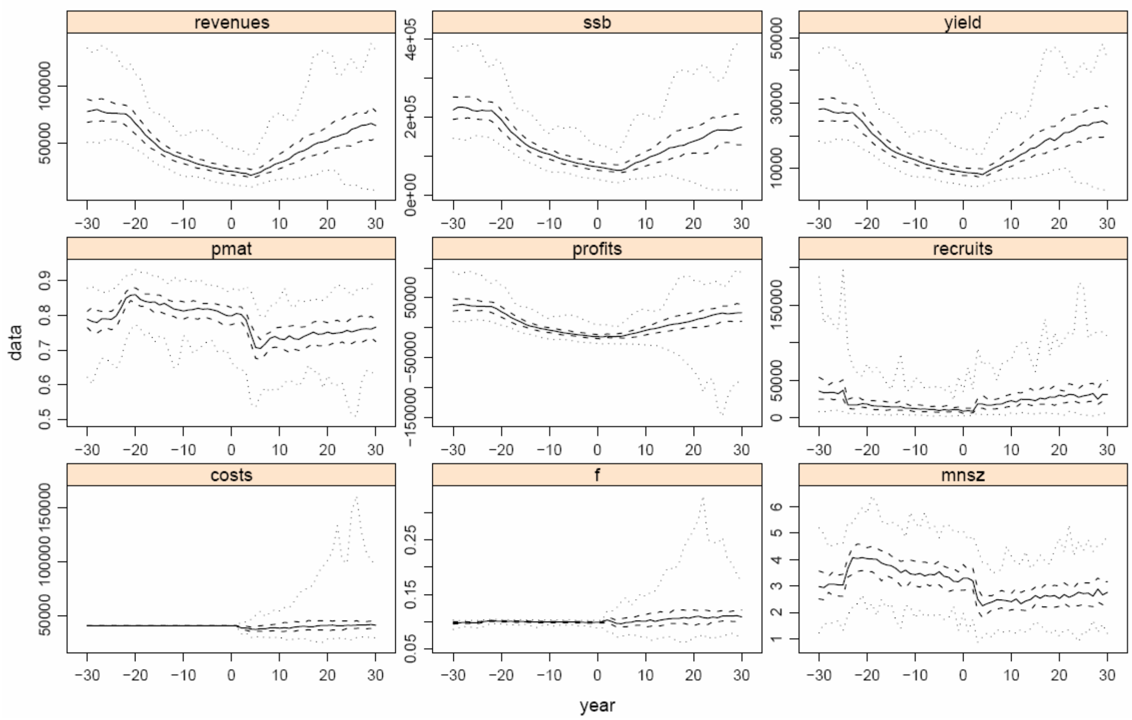

Figure 7j. cod.0.75.3.3.1. A low productivity (steepness = 0.75) overfished cod like stock, with a VPA based HCR with an addition of a change in selectivity for immature fish, and an observation error model that imposes a 30% CV on CE data.

Heroid stock with stock recruitment steepness of 0.75.

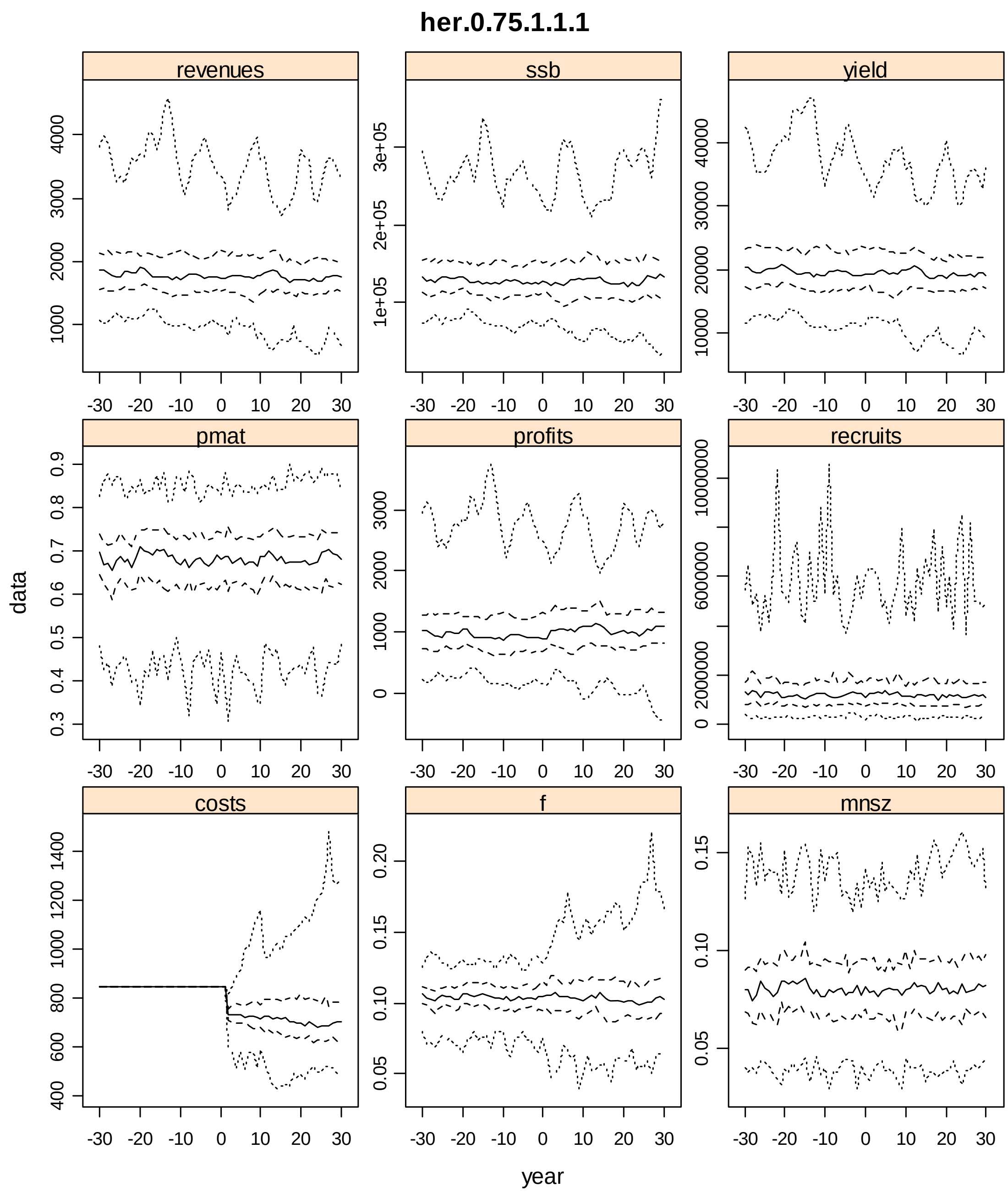

Figure 8a. A well managed heroid stock with a stock recruitment steepness of 0.75, a VPA based HCR that selects the maximum between $F_{0.1}$ and F_{sq}, and an observation error of 30% CV on the CPUE data. There is no effect on fishing mortality except to become somewhat more variable. The HCR appears to maintain the stocks in the condition in which they began the management period.

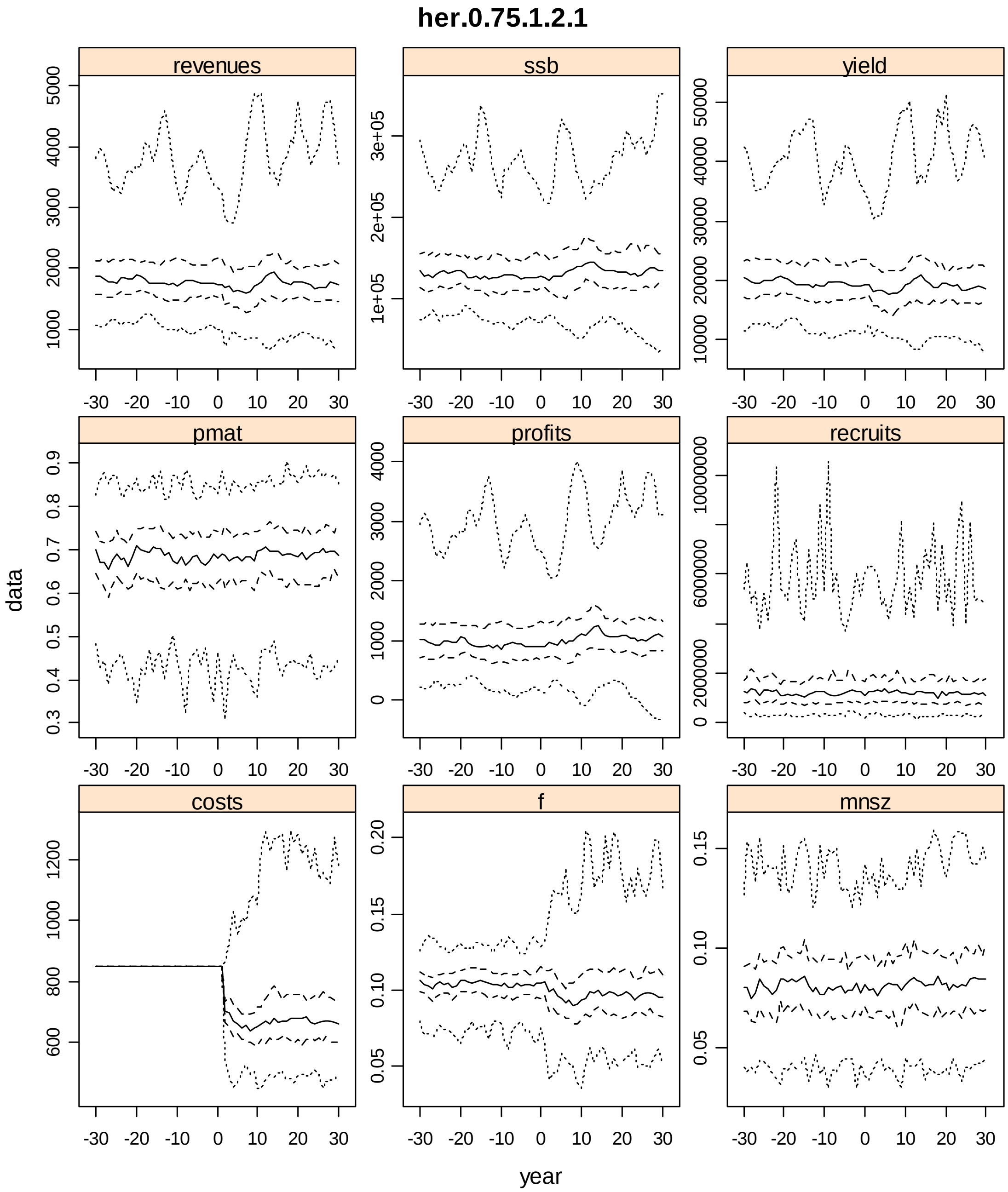

Figure 8b. A well managed heroid stock with a stock recruitment steepness of 0.75, a VPA based HCR that always selects the $F_{0.1}$, and an observation error of 30% CV on the CPUE data. This HCR leads to a small decline in fishing mortality which significantly lowers costs and leads to a slight increase in SSB but no significant increase in yields, or revenue. The decrease in costs leads to an increase in profits. Once again this HCR appears to maintain the stocks in the condition in which they began the management period.

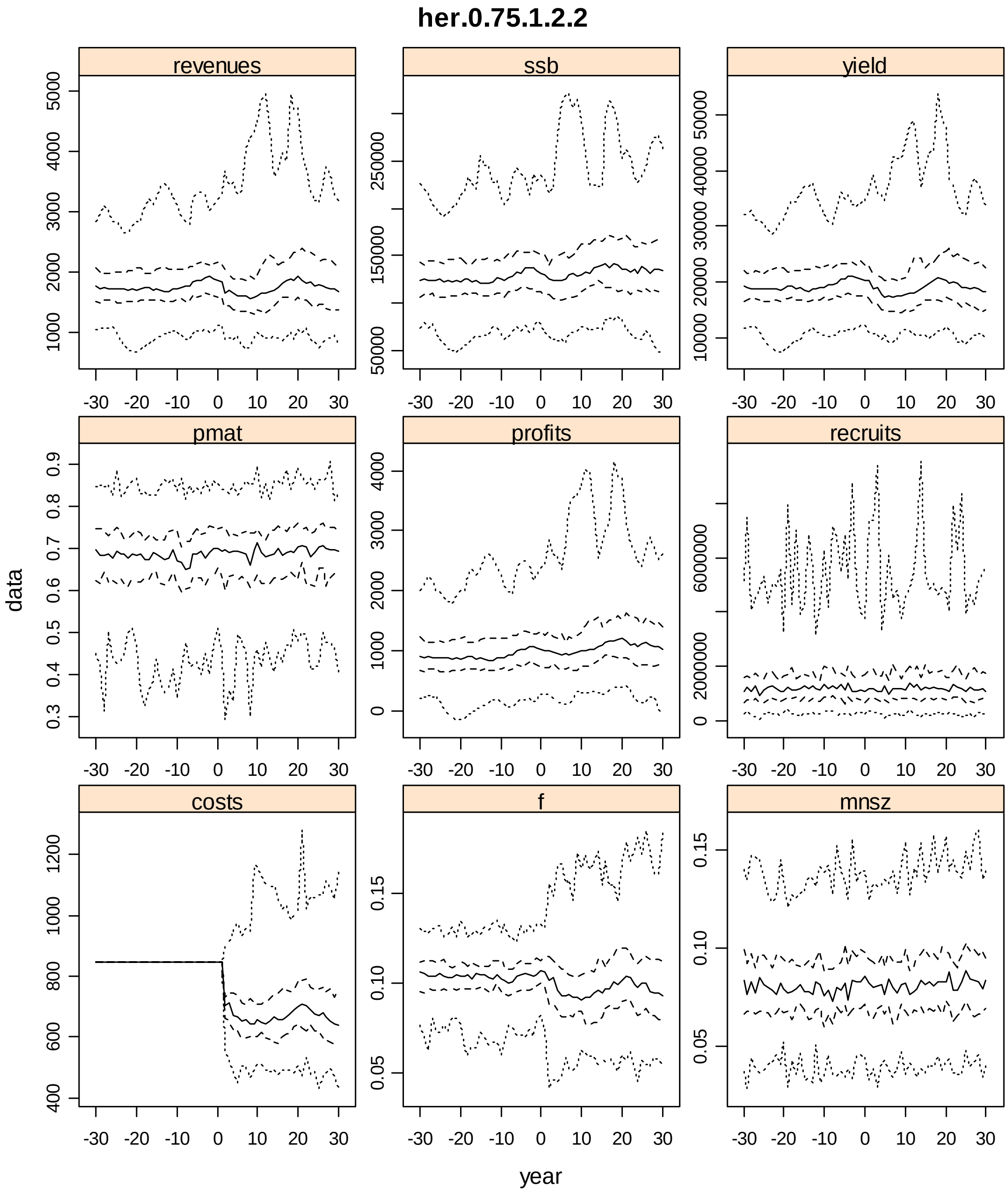

Figure 8c. A well managed heroid stock with a stock recruitment steepness of 0.75, a VPA based HCR that always selects the $F_{0.1}$, and an observation error of 30% CV on the CPUE data plus a linear increase in catchability through time. The effect of the linear increase in catchability through time is only minor on this stock. The reduction in fishing mortality appears similar to that without the linear in crease in catchability but its effect lasts longer. The impacts on costs appear slightly less intense and there are minimal effects on the other statistics, with minor variations matching the changes in the fishing mortality. This HCR appears to maintain the stock in approximately the same condition as when management began.

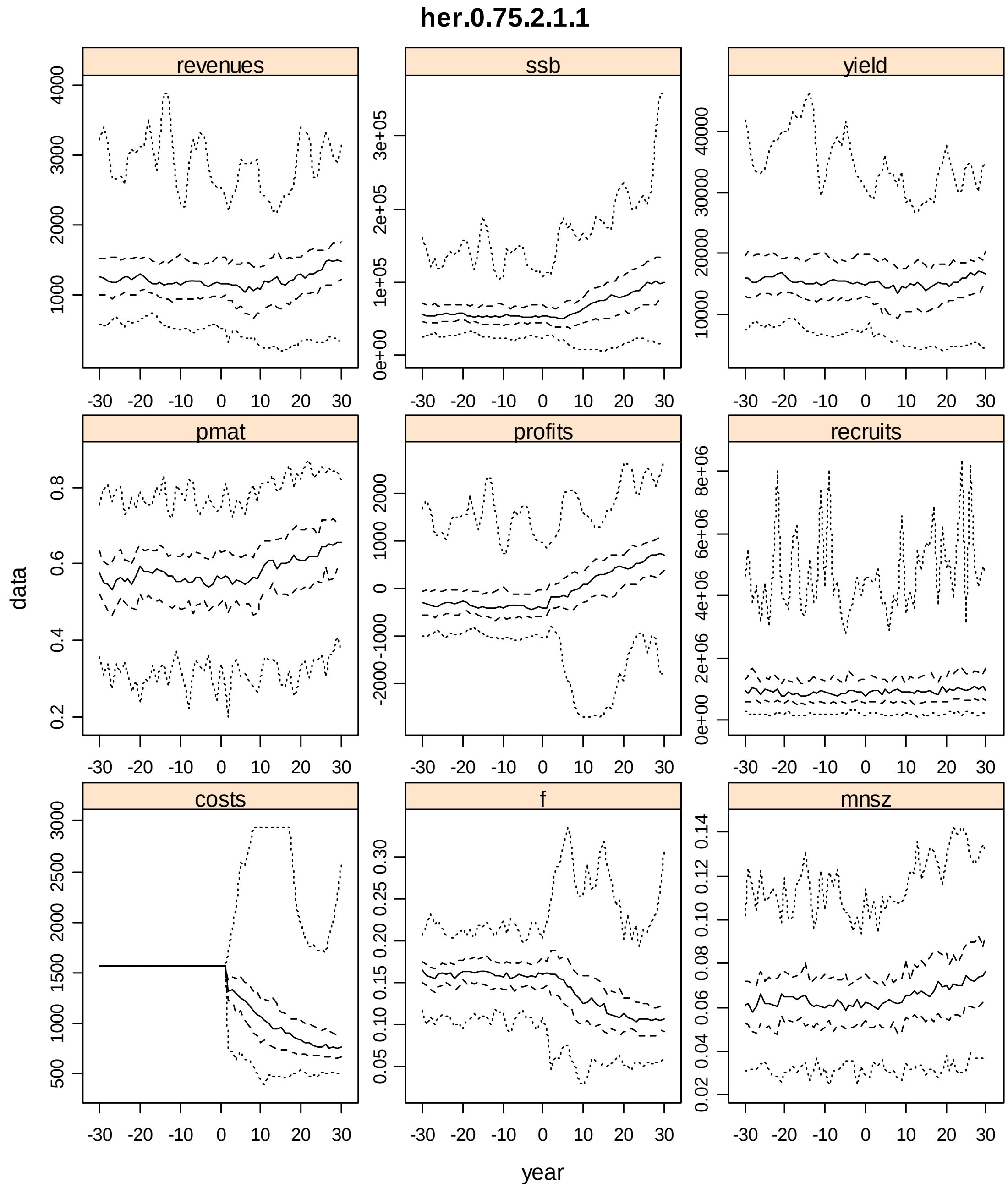

Figure 8d. A heroid stock which is undergoing overfishing with a stock recruitment steepness of 0.75 with a Management Procedure where the maximum of the $F_{0.1}$ and F_{sq}, is taken, while the observation error model includes a 30% CV on the CPUE. In this case fishing mortality gradually declines over a 20 years period leading to, after five years, an increase in SSB which increases revenues, which, in the presence of reduced costs leads t increased profits. There is no obvious effect on yield or recruitment but the mean size increases through time.

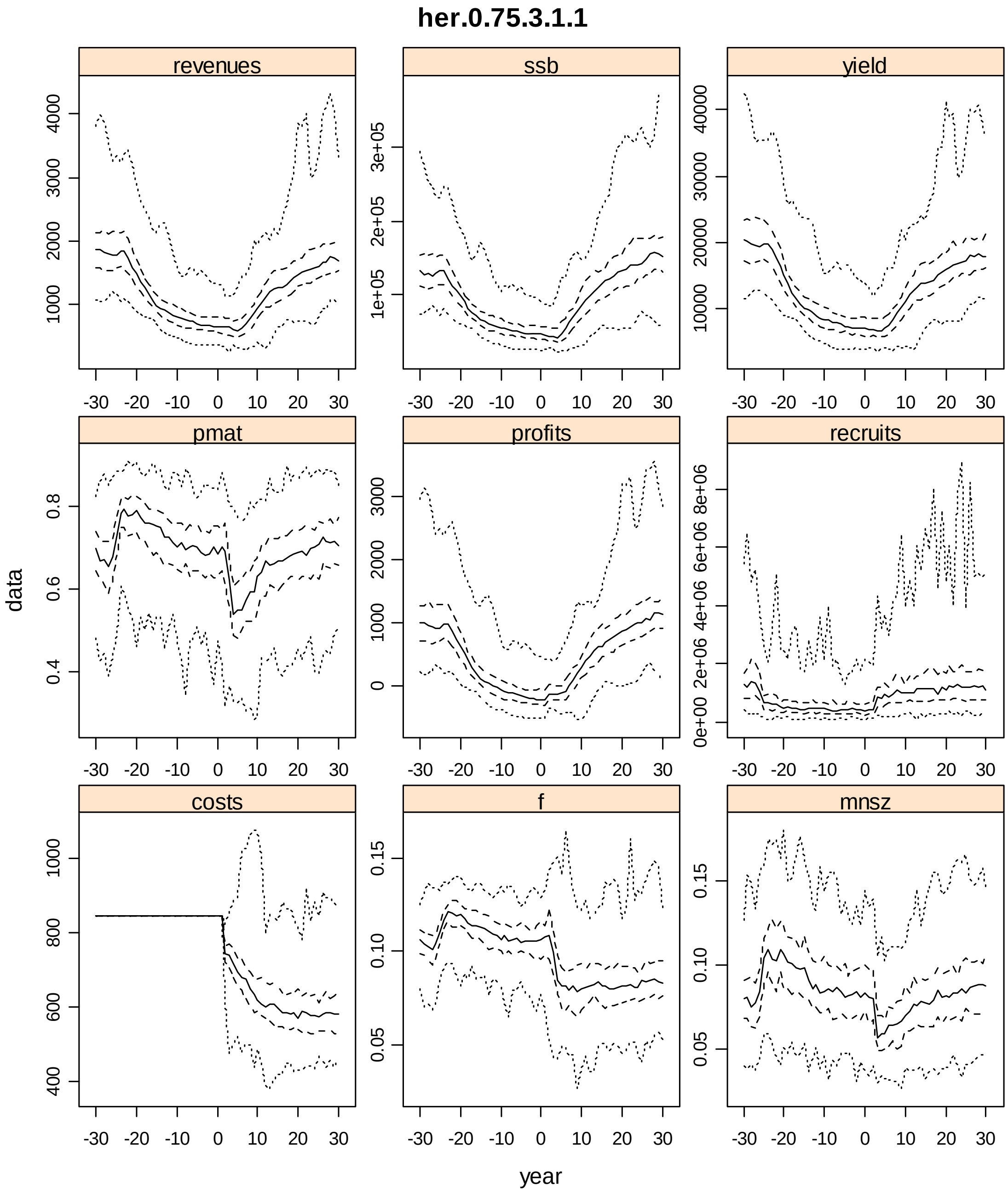

Figure 8e. A heroid stock which is overfished with a stock recruitment steepness of 0.75 with a Management Procedure where the maximum of the $F_{0.1}$ and F_{sq}, is taken, while the observation error model includes a 30% CV on the CPUE. In this case there is an immediate reduction in fishing mortality which, after five years leads to increases in SSB, in yield, revenue, profits, and recruits. Costs decline for ten years and then stabilze. Stock recovery occurs within 20 years.

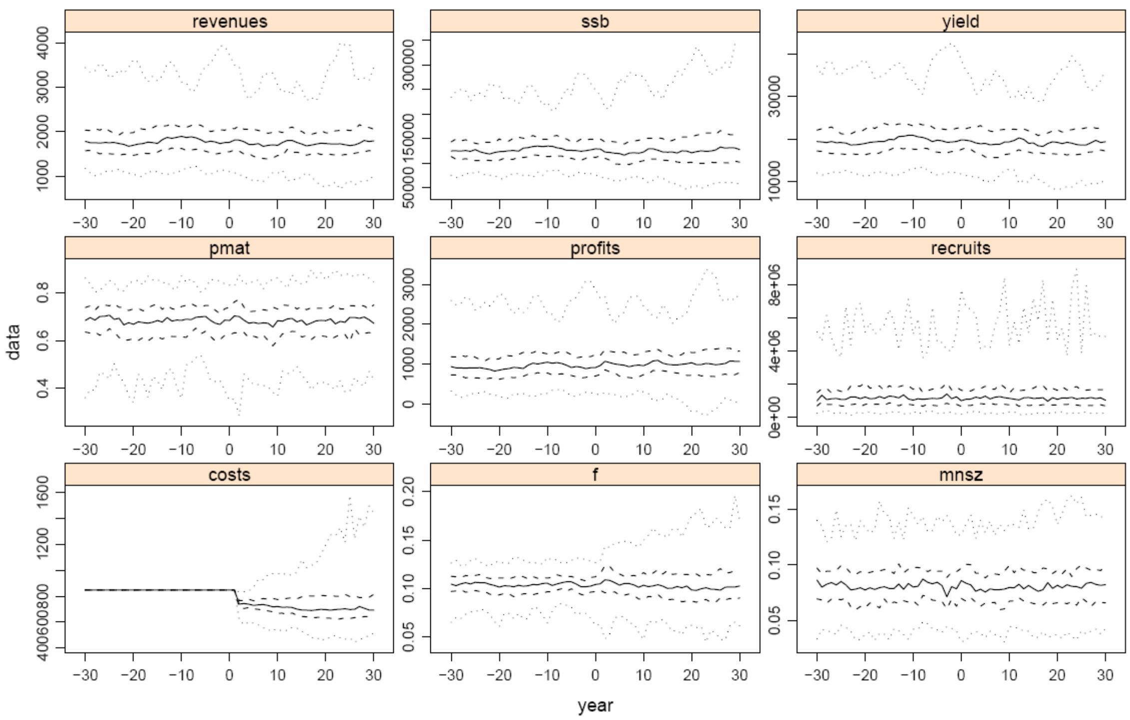

Figure 8f. her.0.75.1.3.1. A well managed low productivity (steepness = 0.75) herring like stock, with a VPA based HCR with an addition of a change in selectivity for immature fish, and an observation error model that imposes a 30% CV on CE data.

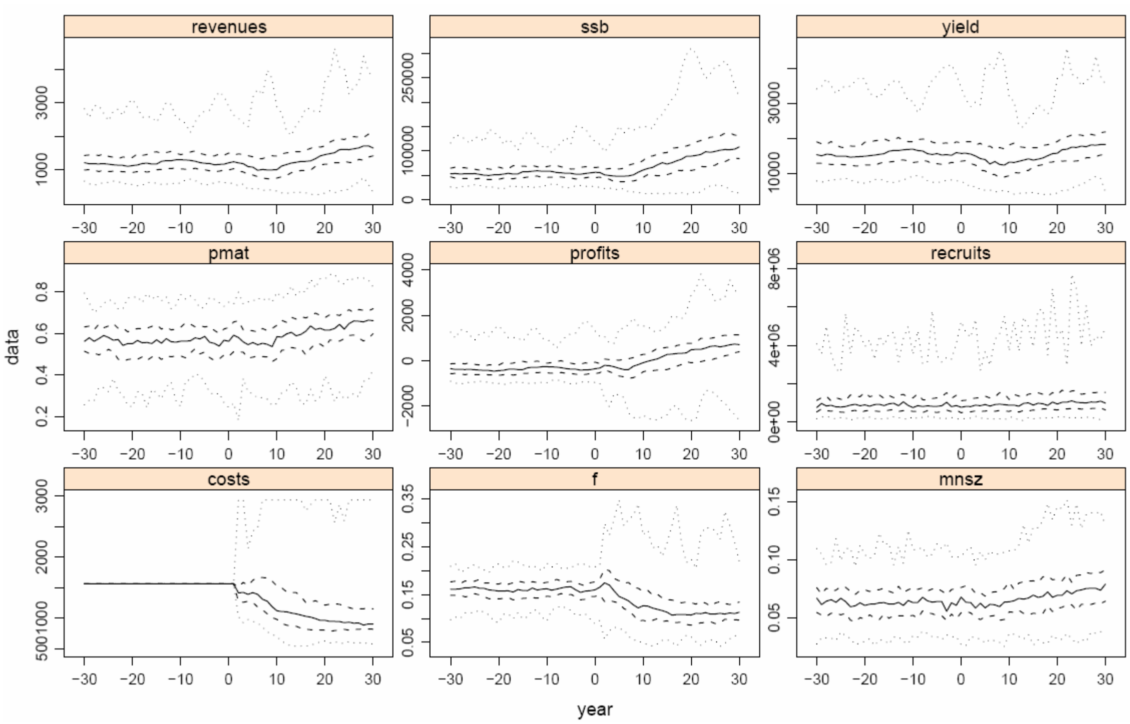

Figure 8g. her.0.75.2.3.1. A low productivity (steepness = 0.75) herring like stock experiencing overfishing, with a VPA based HCR with an addition of a change in selectivity for immature fish, and an observation error model that imposes a 30% CV on CE data.

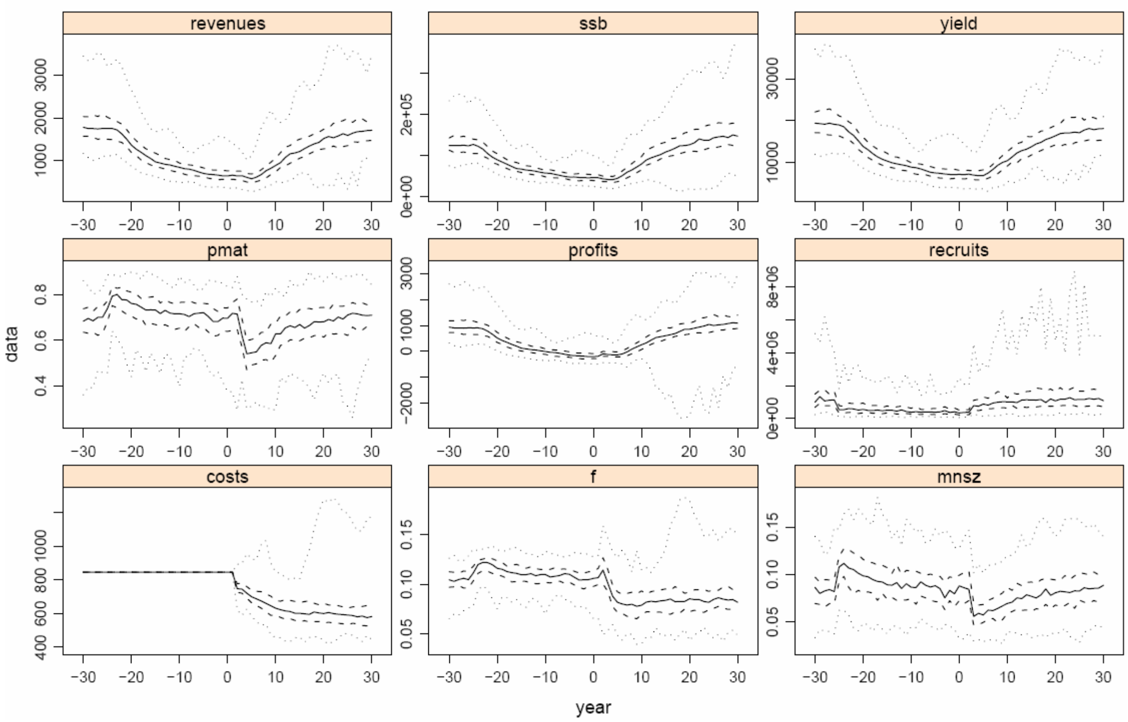

Figure 8h. her.0.75.3.3.1. A low productivity (steepness = 0.75) overfished herring like stock, with a VPA based HCR with an addition of a change in selectivity for immature fish, and an observation error model that imposes a 30% CV on CE data.

Heroid stock with stock recruitment steepness of 0.9

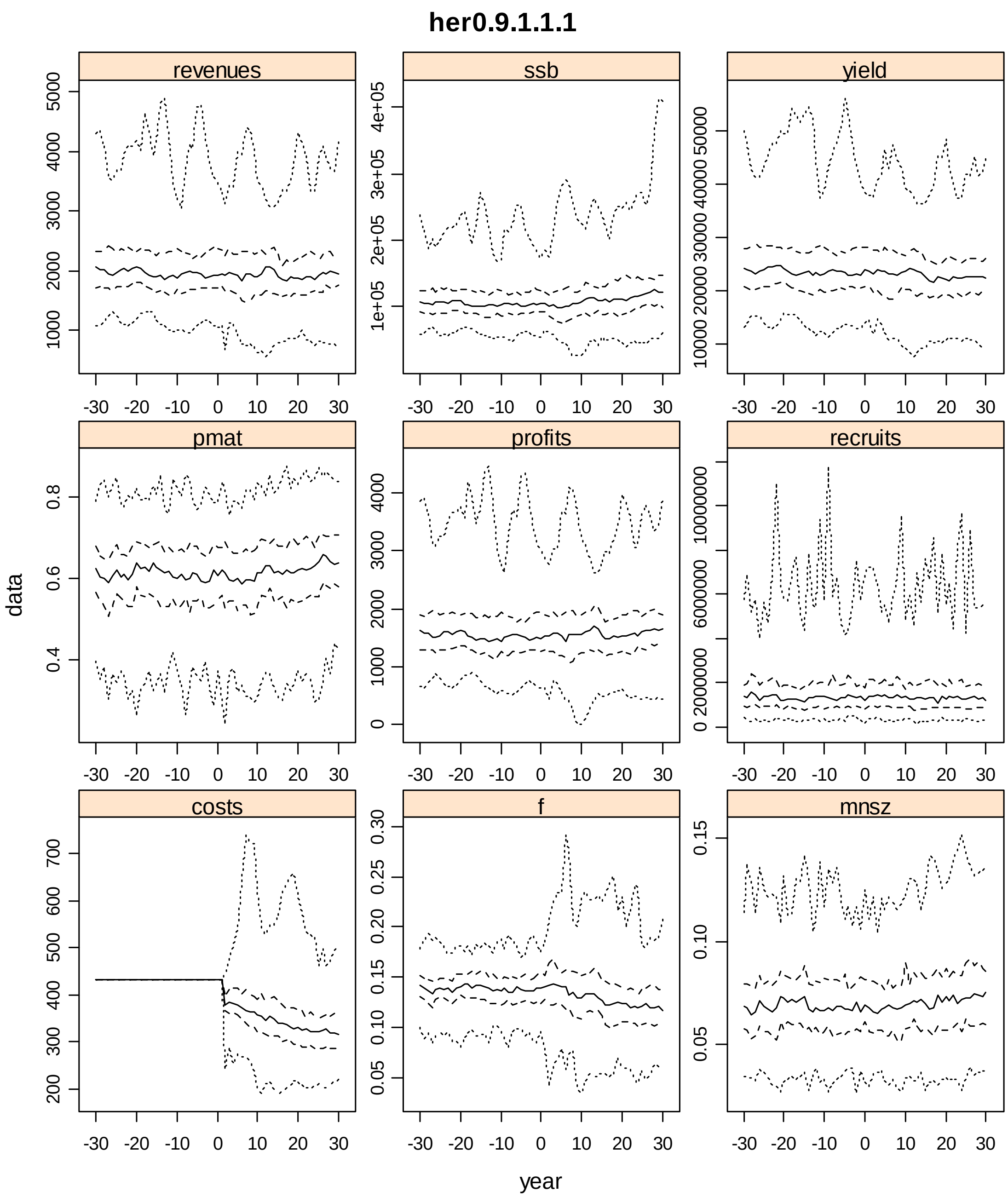

Figure 9a. A well managed heroid stock with a stock recruitment steepness of 0.9 and a HCR that selects the maximum of the $F_{0.1}$ and F_{sq}, while the observation error model includes a 30% CV on the CPUE. There is a slow and small decline in fishing mortality rates which leads to a decline in costs And a slight increase in SSB with a slight rise in profits, mean size, and proportion mature. Otherwise this HCR maintains the stocks in approximately a similar state to the start with only a slight rebuilding.

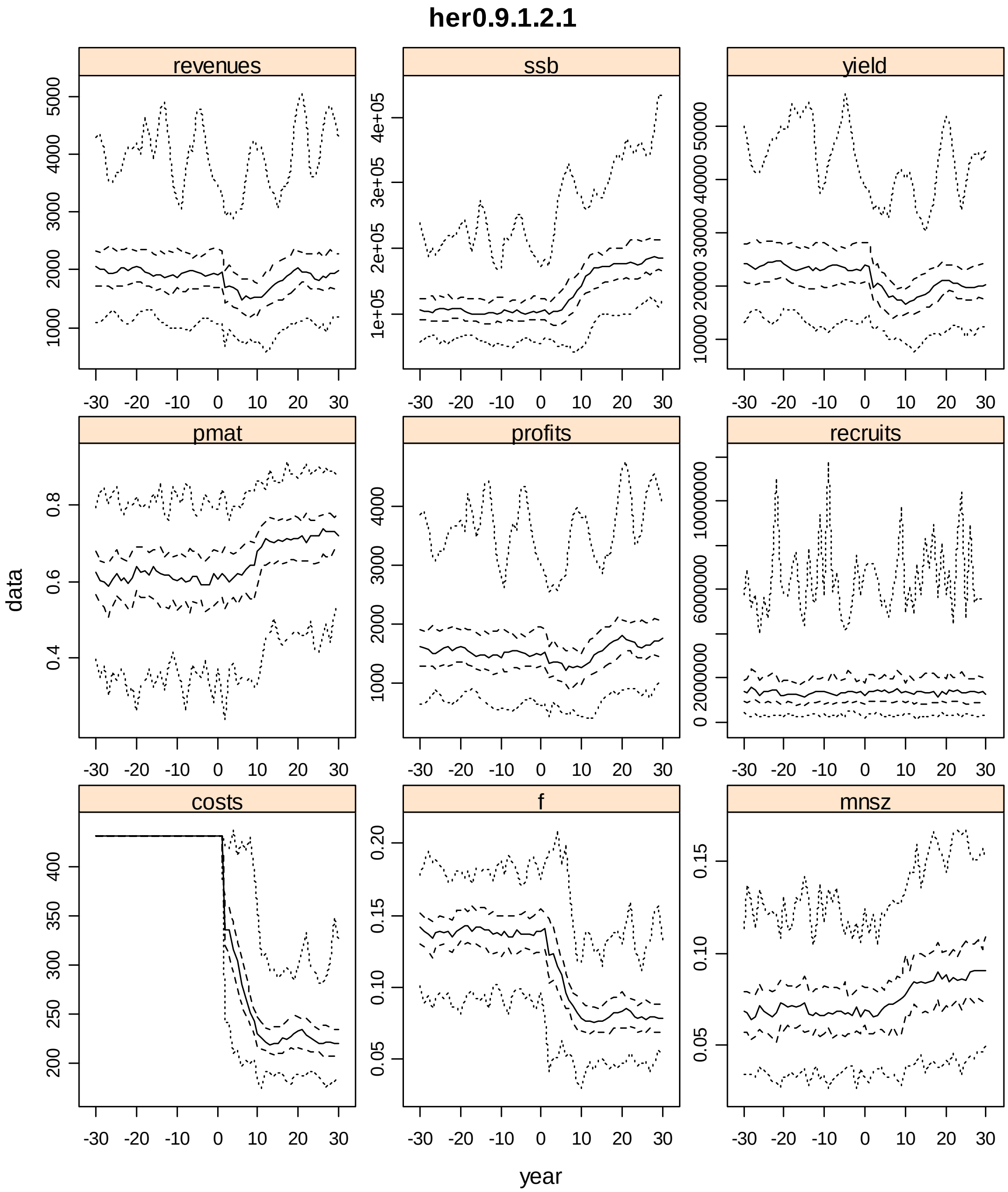

Figure 9b. A well managed heroid stock with a stock recruitment steepness of 0.9 and a HCR that selects the $F_{0.1}$, while the observation error model includes a 30% CV on the CPUE. This HCR leads to a rapid decrease in fishing mortality over a ten year period. The other statistics only respond after between 5 and 10 years so that revenues recover to those at the start, the SSB increases in the first 10 year and then increases at a much slower rate, the yield declines and never regains its original position although the profits increase slightly to a new maximum at 20 years. And mean size increase steadily over the first 20 years.

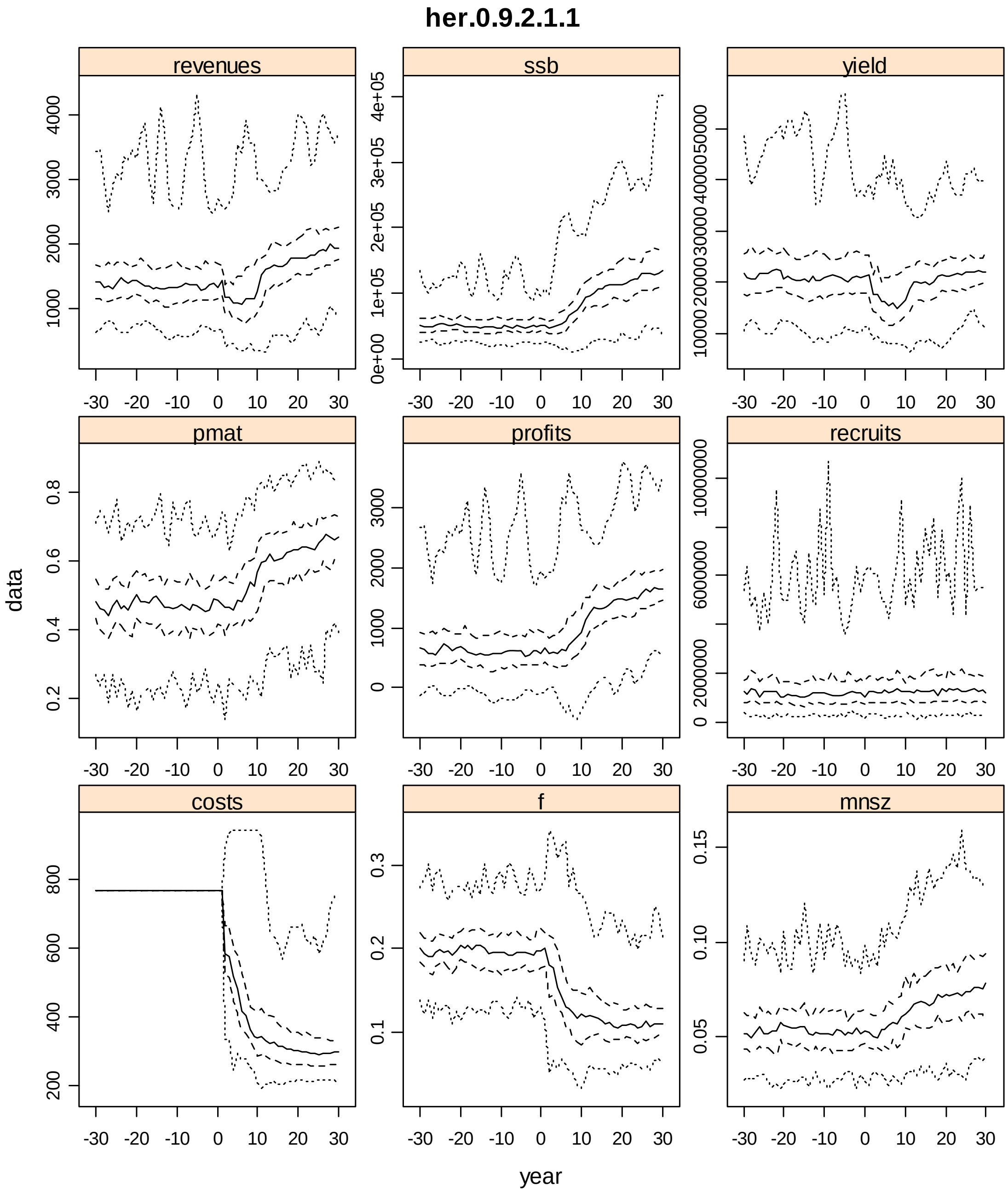

Figure 9c. A high productivity heroid stock (steepness = 0.9) that experienced overfishing and a HCR that selects the maximum of the $F_{0.1}$ and F_{sq}, while the observation error model includes a 30% CV on the CPUE. There was a rapid decline in fishing mortality leading to an immediate decline in yields and revenue, however, costs also dropped rapidly so profits remained stable until they began to increase after about 5 years. This was when the SSB began to increase which led to an increase in the yields until they returned to their initial levels.

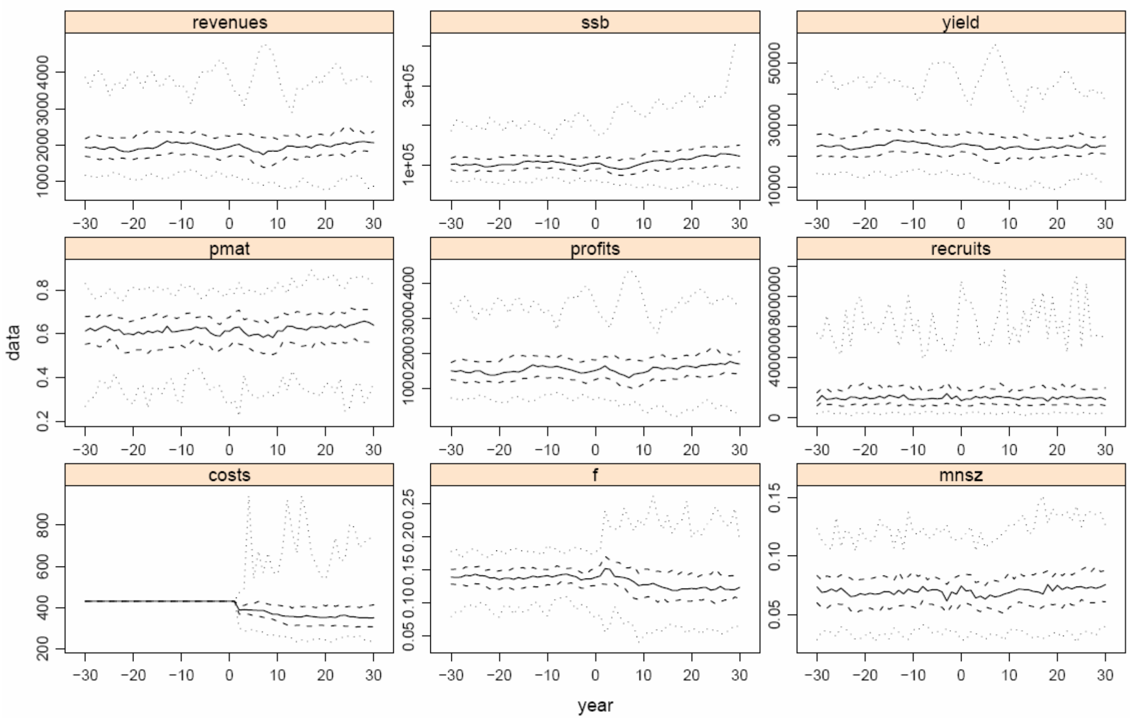

Figure 9d. her.0.9.1.3.1. A well managed, highly productive (steepness = 0.9) herring like stock, with a VPA based HCR with an addition of a change in selectivity for immature fish, and an observation error model that imposes a 30% CV on CE data.

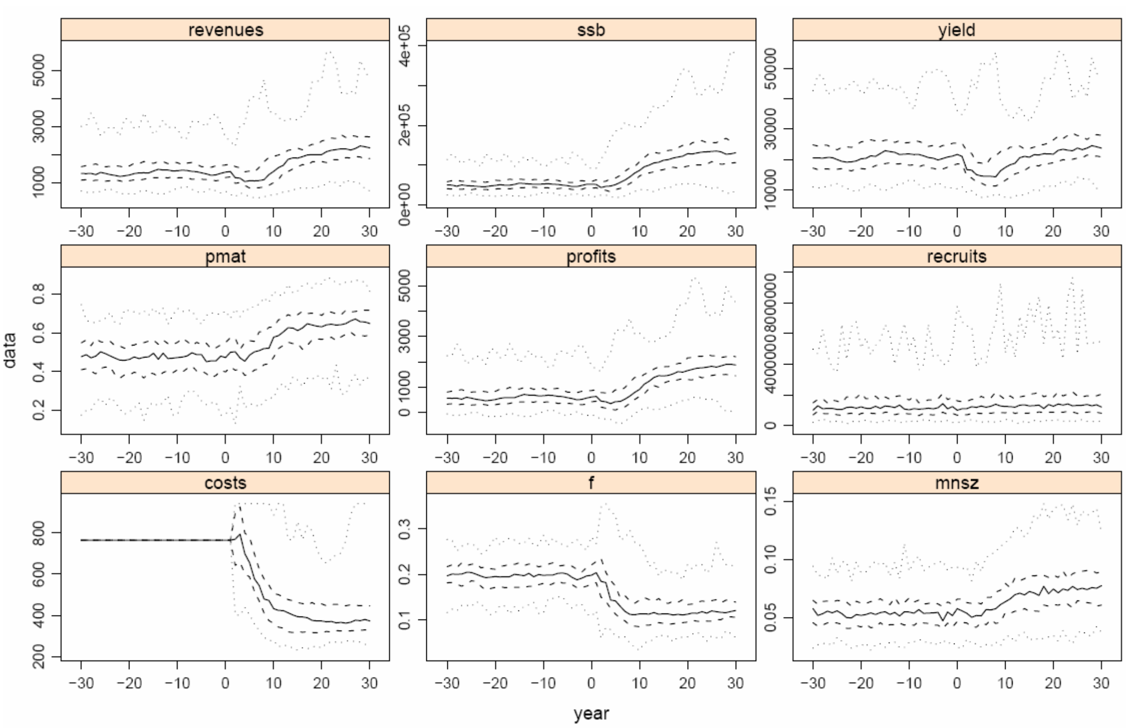

Figure 9e. her.0.9.2.3.1. A highly productive (steepness = 0.9) herring like stock experiencing overfishing, with a VPA based HCR with an addition of a change in selectivity for immature fish, and an observation error model that imposes a 30% CV on CE data.

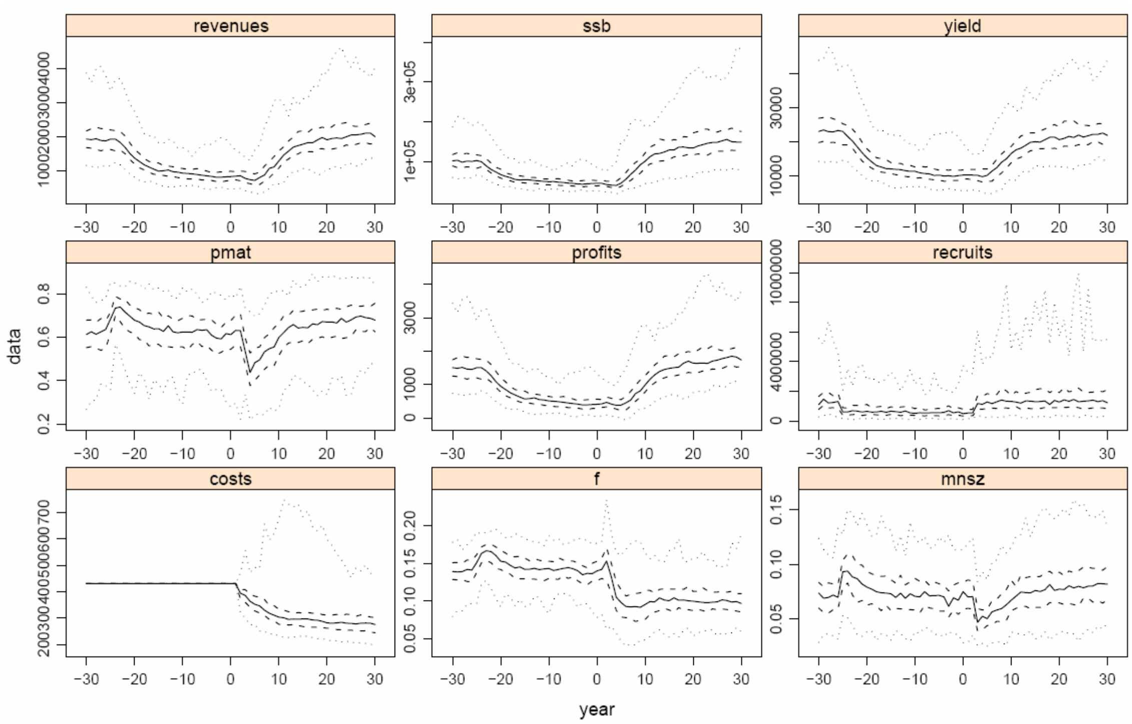

Figure 9f. her.0.9.3.3.1. A highly productive (steepness = 0.9) overfished herring like stock, with a VPA based HCR with an addition of a change in selectivity for immature fish, and an observation error model that imposes a 30% CV on CE data.

Alternative views of the performance of the different can be generated. Various metrics can be examined including:

a) the probability of F being below F_{MSY} P[F<F_{MSY}],
b) probability of negative profits (P[$<0]),
c) probability of profits being above profits at maximum economical yield (P[$>$MEY]),
d) the ratio between profits in a specific year and profits in year 0 ($/$0),
e) the probability of SSB falling below 10 % of B_{MSY}, which is a proxy to stock collapse (P[SSB<0.1B_{MSY}]),
f) the probability of SSB being below B_{MSY} (P[SSB<B_{MSY}]),
g) the probability of a yield decrease related to previous year (P[Y dec]), and
h) the ratio between yield in a specific year and yield in year 0 (Y/Ymsy)

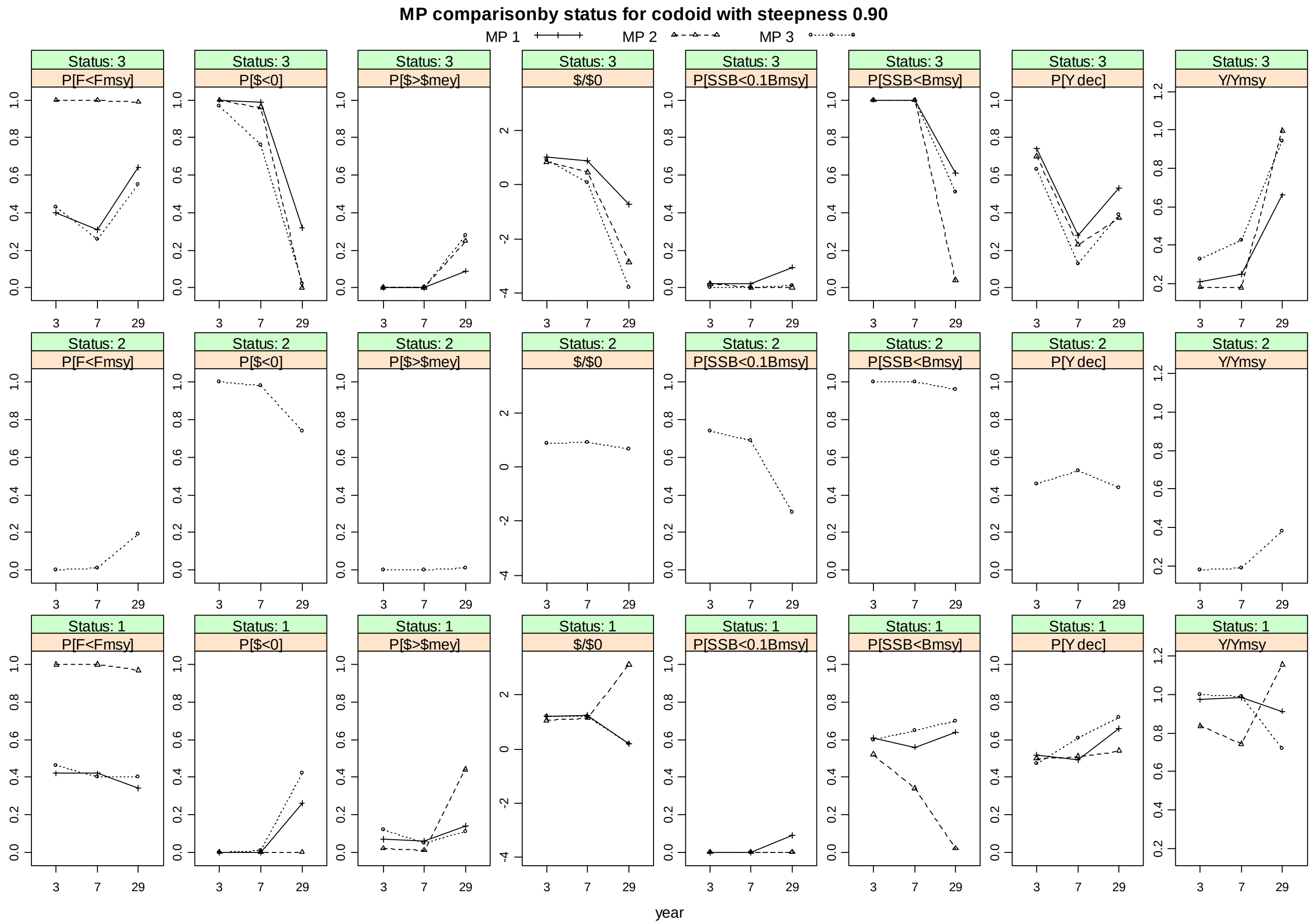

Figure 10. Comparison of Management Procedures for the productive cod-oid stock (steepness = 0.9) across the three initial stock status levels. Status 1 = well managed, 2 = overfishing, 3 = overfished. MP1 = max($F_{0.1}$,F_{sq}), MP2 = $F_{0.1}$, MP3 = MP1 + selectivity change for immature fish.

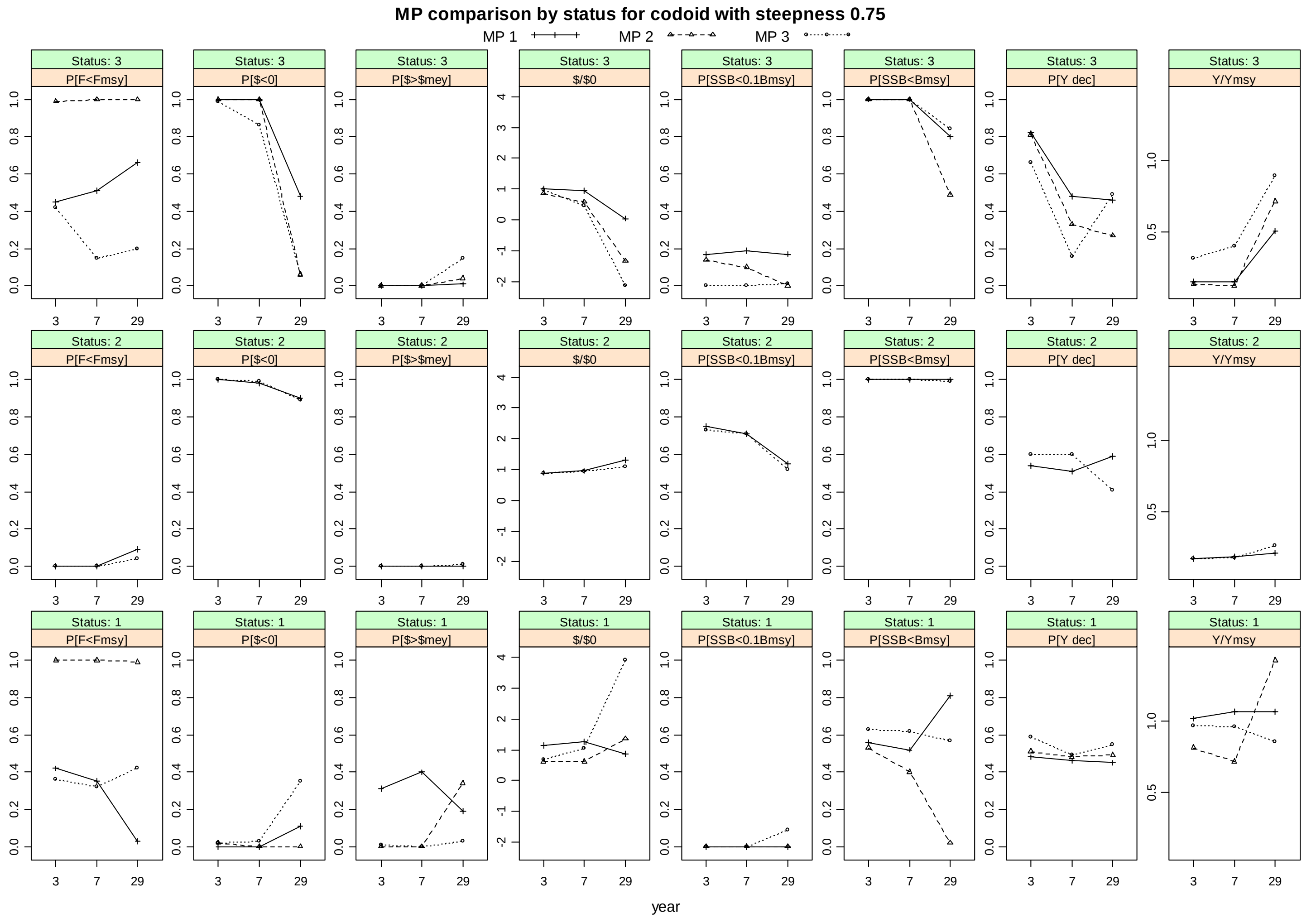

Figure 11. Comparison of Management Procedures for the low productivity cod-oid stock (steepness = 0.75) across the three initial stock status levels. Status 1 = well managed, 2 = overfishing, 3 = overfished. MP1 = max($F_{0.1}$,F_{sq}), MP2 = $F_{0.1}$, MP3 = MP1 + selectivity change for immature fish.

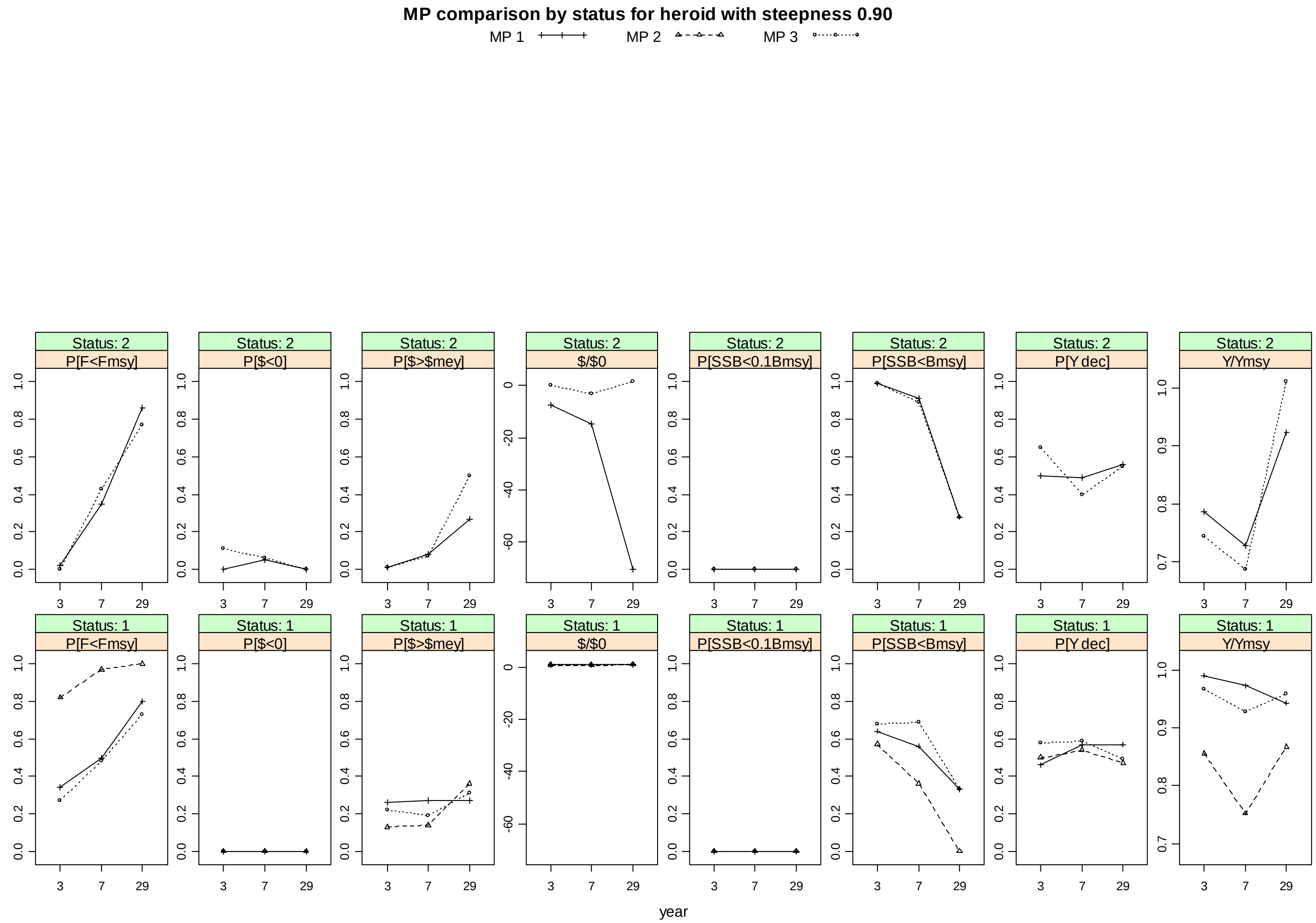

Figure 12. Comparison of Management Procedures for the productive herring like stock (steepness = 0.9) across the three initial stock status levels. Status 1 = well managed, 2 = overfishing, 3 = overfished. MP1 = max($F_{0.1}$,F_{sq}), MP2 = $F_{0.1}$, MP3 = MP1 + selectivity change for immature fish.

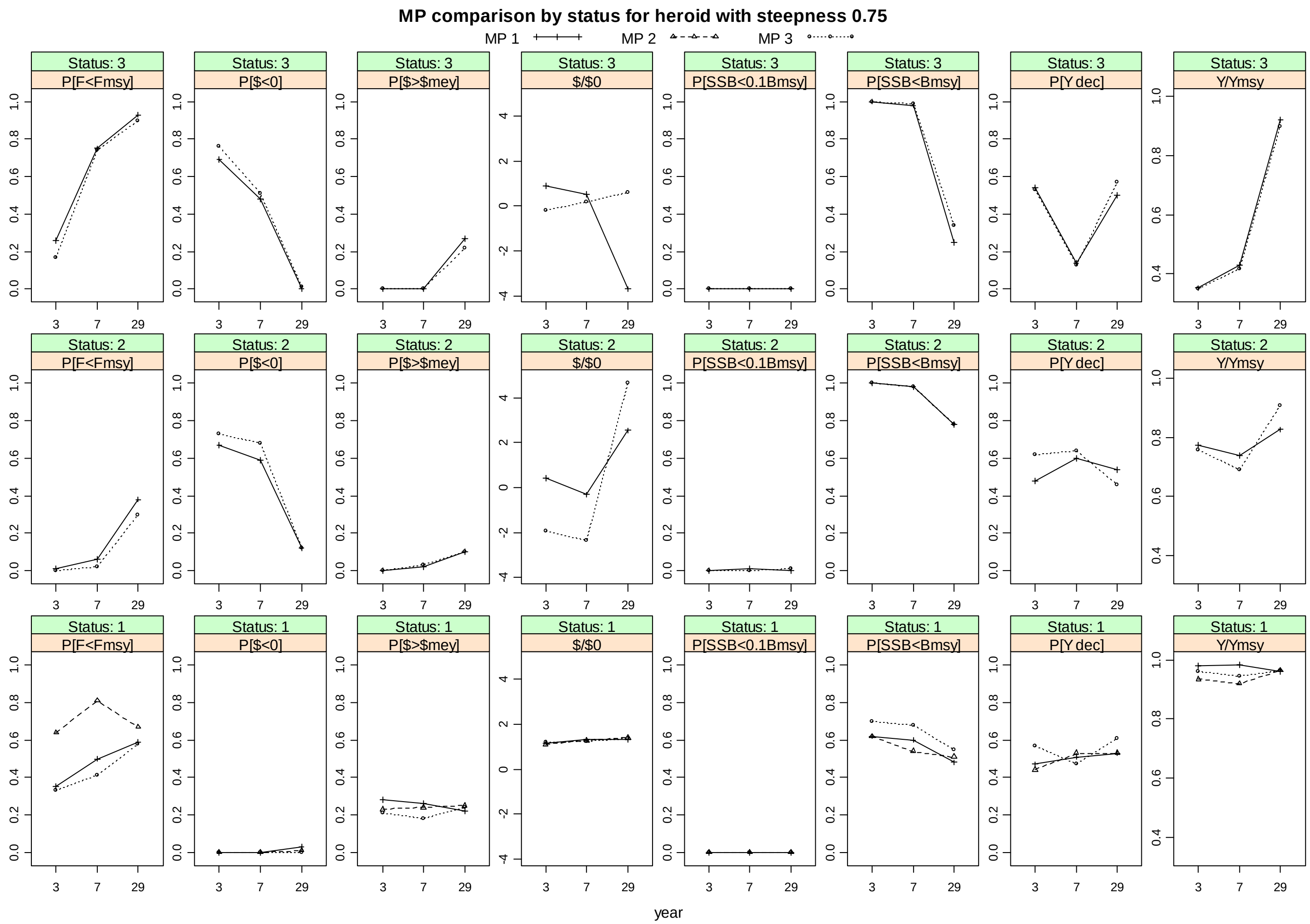

Figure 13. Comparison of Management Procedures for the low productivity herring like stock (steepness = 0.75) across the three initial stock status levels. Status 1 = well managed, 2 = overfishing, 3 = overfished. MP1 = max($F_{0.1}$,F_{sq}), MP2 = $F_{0.1}$, MP3 = MP1 + selectivity change for immature fish.

9. DISCUSSION

9.1. The Scale of the Problem

The scope of the first STECF HCR workshop (Stecf, 2007a,b) was ambitious in that attempting to conduct a full blown Management Strategy Evaluation within the duration of a simple week long workshop had not been done before without considerable preparation. The scope of this second STECF HCR workshop was even more ambitious. Ten cases were presented for exploration and the number of scenarios possible was enormous. This work would not have been possible without the recent developments of the FLR analytical framework, and these workshops have stimulated some significant improvements to the FLR collection.

As with the first HCR workshop, this workshop focused on two generic fish stock types, the cod-oid and the her-oid, each of which were attempting to represent species with markedly different life histories. The simulated populations are not intended to represent any single stock but rather are used to represent a range of different life history characteristics at different levels of exploitation to provide for more extensive testing of the TAC decision rules. The Her-oid and Cod-oid simulated populations represent a range of life-history characteristics, nevertheless there are many stocks that are not covered by this work. Future work may wish to consider long-lived relatively low productivity stocks (such as are found in deep water fisheries) as well as short-lived high productivity stocks (such as squids). Finally, there are many invertebrate stocks whose biology is sufficiently different that it seems likely that they would need their own particular Harvest Control Rules to aid in their management. In addition, this workshop gave only brief consideration to those species for which there is very little data. The model free strategy adopted as a harvest control rule failed to operate successfully and in the simulations where it was applied led to stock collapses and great loss of profits. The principle structure behind a model free HCR was developed but the details are clearly in need of improvement. There remains a limit to what can be achieved within a week long workshop and the development of a suitable harvest control rule for data-poor situations would require further independent work.

9.2. The Harvest Control Rules

Four somewhat different Management Strategies or Procedures were used which implied four different Harvest Control Rules. All analyses were conducted with the assumption of a 30% CV on the fisheries data sampled from the operating model and used in the XSA stock assessments (or the model free rule). In addition, there were a number of scenarios where a retrospective bias was introduced into the data. This was in the form of a linear increase in catchability being applied, which would have had the effect of either increasing or maintaining catch rates even when the stock was in decline. Such retrospective errors are commonly searched for during stock assessments using VPA based methods.

The three based upon the VPA assessment varied in how they responded to the assessment.

The first HCR selected the maximum of $F_{0.1}$ and F_{sq}. The F_{sq} (F-status quo) was often higher than $F_{0.1}$, which meant that with this HCR there was a risk that if overfishing was occurring (fishing mortality was too high) then this HCR might not lead to stock recovery and improvements to revenue and profits. Significantly, even well managed stocks could decline in size and value under this control rule because simple variation encouraged fishing mortality to drift higher; it was easier for fishing mortality to increase than it was for it to decrease. Well managed fisheries could decline under this strategy with the SSB slowly declining along with revenues and profits. Stocks experiencing overfishing did not often recover, remaining at fishing mortality levels that were unsustainable and keeping revenues and profits low. On the other hand, overfished stocks generally improved under this management strategy although only the highly productive stocks were close to recovery even after 30 years. This HCR sometimes led to fishery collapses. The selection of the maximum of $F_{0.1}$ or F_{sq} invariably led to fishing mortality either remaining high or increasing slowly. This led, in turn, to decreases in SSB, and declines in revenue, profits, and yields. This is a risky harvest control rule.

The third management procedure or Harvest Control Rule was a variant on the first. In response to the assessment it selected the maximum of $F_{0.1}$ and F_{sq} but it also decreased the selectivity of the fishing on immature fish. This HCR produced results quite similar to those of the first HCR, however, the effects of the management were often somewhat muted with changes being slightly less dramatic. Generally the effect was to slightly reduce the risk involved in the HCR. For example, the risk of fishery collapse appeared to be less when this variant of the first HCR was used. Nevertheless, this change was not sufficient to remove the risks associated with the first HCR. It would be valuable to consider adding the option of a change in selectivity for immature fish to the second HCR.

The second VPA based HCR always selected $F_{0.1}$, which reduced the risk of fishing mortality drifting higher. Invariably this harvest control rule, once it was imposed, would lead to a reduction in fishing mortality. This often led to a reduction in yield and revenue but fortunately it also led immediately to reduced costs so profits were not always affected badly. The reduction in fishing mortality invariably led to at least some increase in the size of the spawning stock, which in turn led to increases in yield, revenues and profit. However, the decline in yields may take up to 7 years to revert to original levels but they would then tend to increase beyond the original levels of catch. Imposing a bias by adding a linear increase in catchability through time always had the effect of muting or reducing any positive impacts of the HCR, at the same time, fishery collapses became a slight risk. This HCR showed great promise in terms of its ability to maintain stocks at productive and profitable levels, even in the face of retrospective biases. However, there was often a reduction in yields at least for the first few years. Profits did not tend to be badly affected because of the large decrease in costs and both the stock and economic performance improved through time.

The final HCR used a model free rule to determine management options. While the principles required to implement this form of HCR in FLR were developed the actual example control rule that was explored, which compared recent catch rates with the median catch rate from an earlier reference period, failed to provide useful management advice. When applied to a well managed stock the procedure quickly increase fishing mortality, which initially increased yields. However, the procedure failed to respond sufficiently quickly to changed conditions and the SSB rapidly declined in most scenario runs leading to fishery collapse. There remain numerous stocks for which there is very little data available and some model free rule is required to assist with their management. Further dedicated work is required to identify an empirical rule that would work to sustainably manage such stocks.

10. CONCLUSION

10.1. Policy Conclusions

The HCR rule defined in the cases described in the Terms of Reference selects the maximum of $F_{0.1}$ and F_{sq}. This behaves acceptably for overfished stocks, often leading to some rebuilding and recovery. However, it often fails to improve situations where overfishing is occurring and even constitutes a risk to well managed stocks. The rule either maintains fishing mortality at too high a level, preventing recovery, or it leads to a gradual increase in fishing mortality leading to slow stock declines. The HCR can become stuck on relatively high fishing mortality rates that can harm or continue to harm stocks. This occurred because the F_{sq}, while being lower than F_{pa} was still often too high to be sustainable.

By including a change in the selectivity on immature fish the negative effects of this HCR can be slightly muted but not sufficient to enable this HCR to be recommended.

By altering the HCR to select $F_{0.1}$ as the response to each assessment, the HCR became more reliable in terms of maintaining well managed stocks and recovering stocks that had experienced overfishing or were being overfished. This recovery occurred even in the face of a retrospective bias (brought about by a linear increase imposed on catchability through time), although the improvements and level of rebuilding were often reduced. This HCR would often lead to a reduction in yields for the first few years after the introduction of management. However, the significant reduction in fishing mortality led directly to a significant reduction in costs so the profitability of each fishery tended to be maintained.

Within the time constraints of the workshop this HCR was reasonably well examined. However, there were numerous configurations of Operating Model, Management Procedure (HCR), and Observation Error Model that were not considered and before finally recommending this strategy for use in management it would be sensible to complete at least some of the missing combinations. This need not necessarily be done in a workshop environment. It would be a useful addition to consider the effect of including a decrease in the selectivity on immature fish on this version of the VPA based HCRs.

There remain many stocks for which there is little data. The model free HCR examined proved to be incapable of maintaining a well managed stock and so could not be recommended. However, such empirical control rules can now be implemented easily within the FLR framework, so it is recommended that further work be aimed at exploring alternative formulations that might provide positive management advice for data poor situations. In addition, there are many stocks (deep-water species; short-lived species; invertebrate species) for which the present investigations are unlikely to be helpful. It is suggested that further work be focussed on examining the management options for such species.

10.2. Operational Conclusions

The FLR framework has now been developed to a highly usable level. This present work has stimulated the inclusion of an implementation of an auto-differentiation module that speeds many of the assessment calculations. Now 100 iterations within a scenario may take between 20 and 30 minutes rather than 5 to 8 hours as in the previous version. In addition, it has become much easier to implement different harvest control rules and simpler to run the Management Strategy Evaluations.

These improvement mean that Management Strategy Evaluation becomes a serious option for particular species within European fisheries. To date, MSE work has focused on generic fish stocks but now that FLR has reached its current stage of sophistication and speed a useful strategy would be to begin to apply the MSE methodology to particular species and stocks. The complexities of particular fisheries and singular stocks could now be approached within the FLR framework.

11. ACKNOWLEDGEMENTS

Thanks are due to the CEFAS laboratory in Lowestoft for hosting the workshop and providing the necessary facilities. Thanks are also due to the STECF secretariat for their assistance in preparation for this workshop.

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STECF(2007b) STECF working group on Evaluation of "Policy Statement" Harvest Rules REPORT Copenhagen 10 – 14 September 2007. 51 p.

ANNEX II DECLARATIONS OF EXPERTS

Declarations of invited experts are published on the STECF web site on https://stecf.jrc.ec.europa.eu/home together with the final report.

European Commission

EUR 23641 EN **– Joint Research Centre – Institute for the Protection and Security of the Citizen**
Title: Scientific, Technical and Economic Committee for Fisheries. Report of Working Group on Harvest Control Rules (SGRST).
Author(s): Haddon M., Bertignac M., Borges L,. Casey J., Cervino S., Garcia D., Hoelker F., Jardim E., Kell L., De Oliveira J., Payne M., Pomarede M., Tidd A.

Luxembourg: Office for Official Publications of the European Communities
2008 – 87 pp. – 21 x 29.7 cm
EUR – Scientific and Technical Research series – ISSN 1018-5593
ISBN 978-92-79-10478-7
DOI 10.2788/38645

Abstract

For a number of fish stocks, long-term management plans have been agreed and implemented. For those stocks not yet subject to long-term plans, the Commission must propose fishing opportunities that are sustainable inter alia in biological terms. Candidate harvest control rules were evaluated to determine the likely consequences of the application of such rules, for a typical range of biological stock situations currently encountered in Community waters. In total 34 different harvest rule scenarios were evaluated for setting TACs for two generalised fish stocks with different life history parameters. These scenario evaluations fall into two main groups: Evaluations of HCR rules based on the results from analytical assessments and evaluations of HCR rules when no analytical assessment is available. The performance of the harvest control rules are discussed and a number of modifications proposed.

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LB-NA-23641-EN-C

EUROPEAN COMMISSION

ISBN 978-92-79-10478-7

9 789279 104787

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